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NASA TECHNICAL TRANSLATION NASA TT F-15,165

HIGH ALTITUDE AND SPACE SUITS

S. M. Alekseyev and S. P. Umanskiy

(NASA-TT-F-15165) HIGH ALTITUDE AND SPACE SUITS (Scientific Translation Service) 491 p HC $[illegible] CSCL 06K

N74-15797

Unclas
G3/05 27514

Translation of: "Vysotnyye i kosmicheskiye skafandry," Moscow, "Mashinostroyeniye" Press, 1973, 280 pages.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JANUARY 1974

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ANNOTATION

This book generalizes the domestic and foreign experience /2 derived in designing space suits for human high altitude and space flights. The properties of the medium in which the flights take place, the physical flight factors, and their influence upon the human body are discussed. The bases of the theory and method of designing space suit systems and parts are briefly presented.

The book is designed for specialists working in the field of design, production, and testing of equipment for pilots and cosmonauts. It will also be useful to the engineering-technical personnel working on the creation of life support systems for the crews of modern spacecraft, as well as to the students of higher universities.

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FOREWORD

In this book, the authors acquaint the readers with space /3* suit equipment, the principles underlying their operation, and also present reference material which may be useful to designers of space suits and specialists working in the combined fields of aviation and space technology.

Modern space suits are very complex technical devices, many of whose characteristics have not been studied and which are based on engineering intuition. Achievements in the field of space suit construction have still not been adequately discussed in the Soviet literature, and therefore the authors desired to fill this gap to a certain degree.

The first chapter gives brief information on the atmosphere of the Earth and the space surrounding it, which may provide the reader with a concept of the medium in which humans may operate in a space suit.

The second chapter discusses certain physical factors of atmospheric and space flights, and their physiological influence on the human organism (oxygen insufficiency, overloads, ionizing radiation), as well as problems of heat formation and heat output in the human body. Brief data are also presented on human physiology, which are necessary to understand how a space suit operates.

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*Numbers in the margin indicate the pagination of the original foreign text.

The third chapter acquaints the readers with oxygen supply and life support systems for crews on spacecraft, which have been described in the literature. This book also gives brief information on the systems which are also necessary for understanding the operation of space suits.

The fourth chapter describes autonomous systems providing for human life support in a space suit. Since very little experience has been compiled, and is continuously being supplemented, in this completely new field of aviation and space technology, the contents of this chapter are far from complete. When discussing these problems, the authors felt it was necessary to avoid controversial statements.

The fifth chapter examines the equipment and construction /4
of space suits to be used for rescue in case of an emergency, and also gives brief information on designs for the strength of the space suit shell, its ventilation system, and heat protection devices.

The subsequent two chapters — Six and Seven — contain a description of space suits to be used for walking in space and on the surface of the Moon.

The eighth chapter discusses the properties of nonmetallic materials used in space suit construction.

When writing the book, the authors used the advice and comments of many specialists, and would like to thank V. I. Shelyupskiy, V. I. Serenkov, M. K. Vdovchenko, A. S. Barer, L. I. Kuzminskiy, P. I. Zime, M. M. Gudimov, D. P. Trofimovich, V. V. Blokhinaya, Yu. A. Surkov, V. G. Grinev, and T. S. Salamakhovaya, who examined individual sections of the manuscript.

L. A. Bukharin and N. B. Moiseyev provided a great deal of assistance in formulating the book.

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INTRODUCTION

Contemporary aircraft have hermetic cabins in which the pressure, temperature, and other air parameters are maintained at a definite level, providing normal human living conditions throughout high altitude flights. /5

However, during flights on high altitude aircraft or spacecraft, there is a possibility of a sudden drop in the air pressure in the cabin, failures in the supercharging system, collisions with meteorites, and many other emergency situations. In military aviation, it is also possible that the hermetic cabin may be penetrated by missile fragments or air waves.

The crew is in a particularly difficult situation when the hermeticity of the cabin is disturbed at altitudes of more than 6 — 8 kilometers.

At the present time, oxygen masks, high altitude-compensating suits, and space suits are used to protect the crew from oxygen deficiency and low barometric pressure.

When an oxygen mask is used with a special oxygen device, an excess pressure may be produced in the lungs of up to 30 mm Hg, which makes it possible for the pilot to fly briefly at altitudes up to 15 kilometers.

The oxygen pressure in the lungs must be increased even more to maintain satisfactory working conditions at high altitudes. Thus, the necessity has arisen for a compensating suit which facilitates breathing under excess pressure by producing an

external counterpressure over a large portion of the human body by means of tension devices.

A compensating suit with an oxygen mask makes it possible to increase the excess pressure in the lungs up to 75 mm Hg, making it possible for the pilot to fly briefly at an altitude of 16 — 18 kilometers.

The use of a compensating suit with a hermetic helmet, instead of a mask, is a more effective method. Such a device not only normalizes the breathing under excess pressure, but also decreases the stagnation phenomena in the circulatory system. The use of a compensating suit with a hermetic helmet makes it possible to maintain an excess pressure up to 145 mm Hg in the space under the helmet and in the lungs. This enables humans to fly at any altitude, but the time they may remain at high altitudes is limited, in accordance with the data in Table 1. In additional, mechanical tightening, used in a compensating suit, makes it difficult to breathe. It is difficult to provide /6 the necessary counterpressure in the region of the groin, under the muscles, and in certain other locations.

In contrast to a compensating suit, a space suit is pressurized. The pressure maintained in the space suit is uniformly distributed over the entire body and has a favorable influence on the human physiological condition. Therefore, the duration of flights which may be performed in a space suit is much greater than when a compensating suit is used (see Table B.1).

TABLE B.1

PERMISSIBLE "ALTITUDE"* IN AN AIRCRAFT CABIN AND POSSIBLE FLIGHT DURATION WITH THE USE OF OXYGEN DEVICES, COMPENSATING SUITS, AND SPACE SUITS

Type of high altitude equipment	Permissible "altitude" km	Possible flight duration minutes
Oxygen mask without excess pressure	10 11 12	Unlimited 2 — 4 hours to 15
Oxygen mask with excess pressure	15	5 — 10
Compensating suit or vest with oxygen mask with excess pressure	16 — 18	5 — 10
Compensating suit with hermetic helmet	Unlimited	to 15 minutes
Compensating suit with respirator vest and hermetic helmet	Unlimited	Several hours
Space suit	Unlimited	Several tens of hours**

*"Altitude" in the cabin is the standard atmospheric altitude corresponding to the air pressure in the aircraft cabin (GOST 4401-64).

**Flight duration depends on pressure in the space suit, physical load, and individual human characteristics.

A space suit is an all purpose protective device. It protects human beings not only from the harmful influence of a low barometric pressure when the cabin is depressurized, but also from overheating and cooling. In the case of catapulting, it protects man from the impact of the airstream, and when landing on the water, it provides buoyancy and protection from overcooling for a long period of time. However, it is very difficult to produce a space suit which would be very light and would provide good mobility.

The first Ch-1 space suit was designed by Ye. Ye. Chertovskiy in 1931. This was a simple pressurized suit with a helmet, having a small viewing window. No hinges were included in its design. When the space suit was supercharged, great efforts were required to bend the hands and legs, and therefore it was impossible to work in the space suit when there was an excess pressure in it [4, 5].

The space suit Ch-2 (1932 — 1934) had hinges at the bending points of the extremities, due to which it was possible (although to a limited degree) to bend the arms and legs. However, the problems of human life support were still not solved in these space suits [1].

The space suit Ch-3 (Figure B.1), which was developed in 1935 — 1937, encompassed all the basic elements of future space suits, and also took into account the physiological-hygienic requirements. /7

At an excess pressure of 0.1 — 0.15 kG/cm^2*, a pilot in a space suit made of rubberized fabric can move about and control the aircraft. After tests in a barometric chamber, test pilot S. Korobkov performed flight tests in a space suit at altitudes up to 12 kilometers. Flight physiologists V. A. Spasskiy and A. P. Apollonov [3] participated in the development of the space suit Ch-3.

In 1938 and 1939, Ye. Ye. Chertovskiy designed space suits Ch-4 and Ch-5, and in 1940 he produced the improved designs of space suits Ch-6 and Ch-7. Ye. Ye. Chertovskiy was the first individual in the Soviet Union to design a high altitude space suit. In 1937, the Central Committee of the Society for Assistance to the Defense, Aviation, and Chemical Construction

*Translator's Note: kG designates kilogram force.

Figure B.1. Ch-3 high altitude space suit (1935 — 1937).

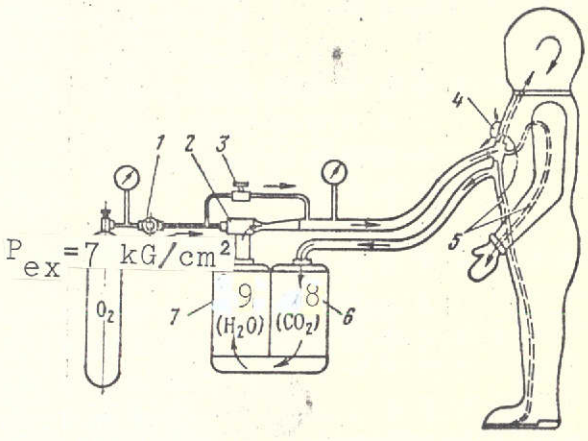

Figure B.2. Block diagram of "SK-TsAGI-2" space suit regeneration system.

1 — reducer; 2 — injector; 3 — emergency supply stopcock; 4 — manometer for pressure measurement at space suit input; 5 — ventilation system tubes; 6 — CO_2 absorber; 7 — drainage container; 8 — lime chemical absorbent; 9 — silica gel.

of the USSR awarded him a prize for solving the problem of spacecraft mobility.

In contrast to the well-known foreign space suits, designed for brief flights in order to establish a world record, the first Soviet space suits were designed so that man could remain in them for several hours in the stratosphere. They were equipped with an autonomous oxygen supply system, of the regeneration type, making it possible for the crew to detach themselves from it and move about in the aircraft from one place to another, or to bail out with a parachute.

Soviet space suits have also been developed in the Central Aerodynamic Institute (TsAGI) under the leadership of A. I. Boyko and A. I. Khromushkin (the latter led the development of a life support system for space suits).

The first experimental space suit, under the name of Sk-TsAGI-1, was developed, built, and tested in 1937. It consisted of upper and lower parts, connected by means of a metallic belt connection. Shoulder hinges provided the necessary mobility for the arms. The space suit covering was made of a two-layer rubberized fabric.

In 1938, the SK-TsAGI-2 regeneration type space suit was developed, which operated at a pressure of 0.3 kG/cm^2.

The autonomous regeneration system was designed to operate for six hours (Figure B.2). In this system, air from the space suit entered regeneration containers, in which it was purified from carbon dioxide and water vapors. The purified air was directed into an injector, where it was mixed with oxygen continuously supplied from a tank, and then was again fed into the space suit. A large portion of the air supplied to the space suit from the injector entered the helmet for breathing, and a small part entered underneath the space suit to ventilate the trunk, arms, and legs. Pressure in the space suit was maintained by a regulator.

At the end of 1938, an improved SK-TsAGI-4 space suit was developed, which was tested in a barometric heat chamber.

In 1940, the space suits SK-TsAGI-5 and SK-TsAGI-8 were developed, based on the accumulated experience (Figure B.3).

The SK-TsAGI-8 space suit was tested on the Soviet I-153 fighter plane, which did not have a pressurized cabin or a protective canopy.

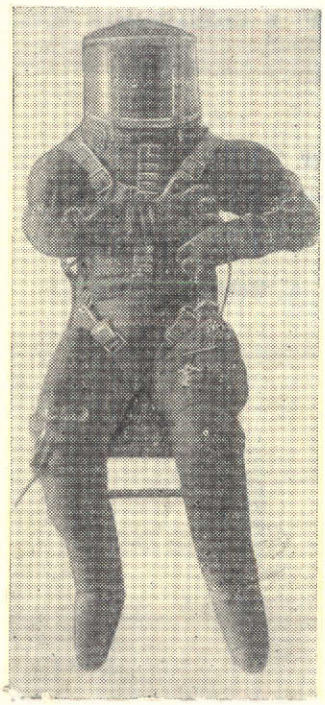

Figure B.3.
SK-TsAGI-8 aviation space suit (1940).

During the Great Patriotic War, the development of space suits was suspended.

The post war period was characterized by the rapid development of jet aviation, making it possible to increase the flight data on aircraft. /8

The flight altitude of jet aircraft significantly exceeded the altitude at which a pilot with an oxygen mask was physiologically able to fly the aircraft. Therefore, jet aircraft were built with pressurized cabins. Whereas previously a space suit was the only way for human beings to function at high altitudes, now — with a pressurized cabin — different requirements were imposed upon it. Thus, in a pressurized cabin, a space suit must not restrict movements, reduce the control over the aircraft, or impair the vision. In a depressurized cabin, the space suit must automatically begin to operate and provide the necessary living conditions for the pilot.

Taking these requirements into account, in 1947 — 1950 a group of designers under the leadership of A. I. Boyko developed the VSS-01 and VSS-04 high altitude rescue space suits (Figure B.4). These types of space suits were in the form of a pressurized suit made of rubberized fabric, with a helmet attached to it which could be pushed back, and an oxygen mask. The sleeves and trousers had hinges, and the power system kept the space suit from "expanding." The pressure in the space suit was controlled by an excess pressure valve. The upper part of the

Figure B.4. VSS-04 high altitude rescue space suit (1950).

a — without outer covering; b — with outer covering and helmet thrown back; 1 — pressure regulator; 2 — lacing for adjusting the size of the space suit; 3 — connecting joint; 4 — combined joint for the hoses (oxygen breathing supply to the helmet, air supply for ventilation of the trunk and extremities, compensating hose of the oxygen device).

space suit had a neck opening in order to put on the space suit.

The onboard oxygen system consisted of a KP-16 device (later called KP-18). Supercharging and ventilation of the space suit was carried out by the jet engine compressor.

In order to leave the aircraft at a high altitude in an emergency, the pilot had a KP-23 parachute oxygen device.

Space suits were developed for space flights by Soviet scientists and engineers. On April 12, 1961, Yu. A. Gagarin completed the first space flight in history in a space suit whose purpose was to maintain the cosmonauts vital activity if the cabin were depressurized.

On March 18, 1965, A. A. Leonov made the first walk in space.

Thus, at the present time, there are three types of space suits:

— emergency-rescue (aviation and space);

— for walking in space;

— for walking on the surface of the Moon.

Space suits will be developed in the future for walking on the surface of Mars, Venus, and other planets.

Life support systems have also been developed which maintain a given microclimate in the space suits. In emergency-rescue space suits, these systems are usually combined with the aircraft air conditioning systems, and in other cases, they are autonomous and are carried in special packs which the cosmonauts wear. /9

The construction of the space suits may be divided into *soft*, *rigid*, and *semi-rigid*.

The covering for soft space suits is made of special fabrics, and does not hold its shape when there is no internal pressure. When an internal pressure is developed, this covering acquires a certain rigidity and can absorb bending moments and torques.

Rigid space suits are made of materials which hold their shape under operational and nonoperational conditions (metals, solid plastics).

In semi-rigid space suits, the body is made of metal, and the "extremities" are made of fabric.

Space suits may be divided into *ventilation* and *regeneration* space suits based on the method by which gas is supplied for ventilation and breathing.

In a ventilation space suit, the air which is necessary for ventilation and maintenance of an internal excess pressure is supplied from an air compressor of the aircraft engine, and the oxygen for breathing is supplied from oxygen sources on the aircraft.

During flights in a pressurized cabin, excess pressure cannot be produced underneath such a space suit, and the respiration products, together with the ventilation air, pass without hindrance to the outside through the pressure regulator. In the case of a depressurized cabin, the pressure regulator automati- /10
cally produces a given absolute pressure in the space suit.

In contrast to ventilation space suits, regeneration space suits operate along a closed cycle, in which the exhaled and exhausted ventilation air is not passed to the outside, but passes through containers which absorb the carbon dioxide and the moisture. This air is enriched with oxygen and is again passed into the space suit.

Space suits are divided into *mask* and *maskless* space suits, depending on the method by which oxygen is supplied for breathing.

The oxygen is supplied only to the mask in a mask space suit, and in a maskless space suit, the oxygen directly enters the space underneath the helmet.

REFERENCES

1. Grishanov, N. G. and S. P. Umanskiy. Space Suits for Pilots and Cosmonauts. Aviatsiya i kosmonavtika, 1965, No. 7.

2. Spasskiy, V. A. Fiziologo-gigiyenicheskoye obespecheniye poletov v skafandre (Physiological-Hygienic Flight Conditions in a Space Suit). Moscow, Medgiz, 1940.

3. Pereskokov, A., P. Yegorov, and M. Rayevskiy. Potolok letchik (Flight Ceiling). Moscow, Voyenizdat, 1931.

4. Chertovskoy, Ye. Ye. Stratosfernyye skafandry (Stratosphere Space Suits). Moscow, Voyenizdat, 1940.

5. Chertovskoy, Ye. Ye. Stratostaty (Stratosphere Balloons). Moscow, Ob'yedinennoye nauchno-teknicheskoye izdatel'stvo (ONTI), 1936.

CHAPTER 1
BASIC CHARACTERISTICS OF THE PLANETS IN THE SOLAR SYSTEM AND INTERPLANETARY SPACE

To become familiar with the conditions under which space suits are used, we shall give certain information on the Earth and planets, to which flights are planned in the near future, as well as information on interplanetary space. /11

1. Sun

The structure of the Sun has been studied comparatively little. Its visible surface is called the photosphere. The chromosphere is located above the photosphere. The outer covering of the Sun, the solar corona, is located above the chromosphere.

The chromosphere is a layer of the atmosphere which is 10,000 — 15,000 kilometers wide, with a very rapid decrease in pressure along the vertical layer [1].

The solar corona is a very wide and rarefied layer which extends above the chromosphere to a distance equal to several solar radii. The temperature of gases in the upper part of the corona is on the order of 10^{6}° K, and the temperature of the photosphere is 5750° K.

The integral flux of solar radiation energy (solar constant of the Earth) at a distance corresponding to an orbit of the Earth (outside of its atmosphere) and on the surface of the Moon is

$$I_0 = I_s \left(\frac{R_s}{R_{orb.e}} \right)^2 \approx 1200 \quad \text{kcal/(m}^2 \cdot \text{hr)} \qquad (1.1)$$

where R_s is the radius of the solar photosphere surface (R_s = $0.696 \cdot 10^6$ km); $R_{orb.e}$ — mean radius of the Earth's orbit ($R_{orb.e}$ = $150 \cdot 10^6$ km); I_s — specific energy liberation of the photosphere.

Formula (1.1) may be used to determine the solar constant for the orbits of other planets in the solar system, and at any point in interplanetary space, replacing $R_{orb.e}$ in it by the appropriate radius.

Approximately 41% of the solar energy belongs to the visible portion of the spectrum, 51% — to the infrared portion, and 8% — to the ultraviolet portion. In the ultraviolet portion of the spectrum, there is a very small amount of energy from the shortest waves (up to 2000 Å).

Dark regions are sometimes observed on the surface of the Sun, which are called solar spots. The number of the spots and their dimensions periodically change.

The amount of solar spots and their characteristics characterize to a certain extent the solar activity and the intensity of ionizing solar radiation corresponding to it.

Shortwave solar radiation (with wavelengths less than 3000 Å) barely reaches the surface of the Earth. Radiation in the 2000 — 3000 Å range is basically absorbed by nitrogen, and waves with a length of 800 — 2000 Å are absorbed by molecular oxygen. /12

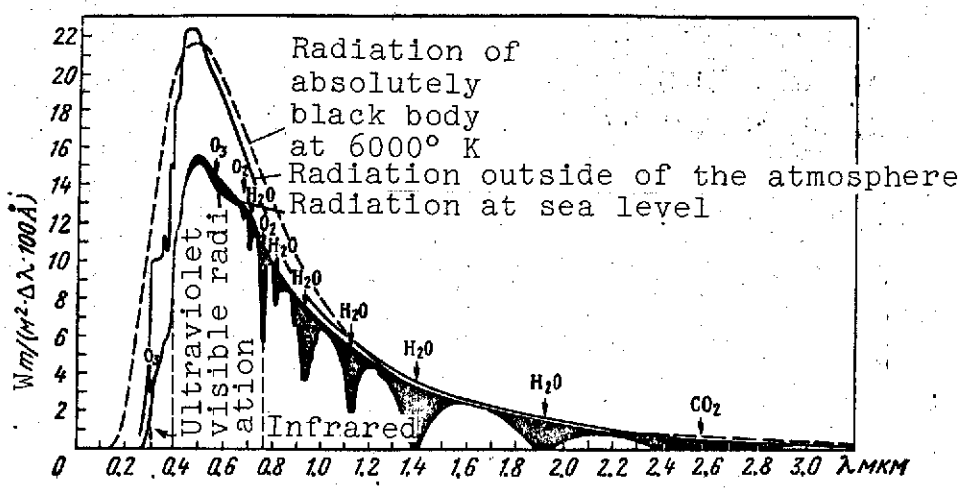

Figure 1.1. General energy distribution in the solar radiation spectrum on a clear day when the Sun is close to the zenith (arrows indicate the regions and intensity of solar radiation absorption by gases and vapors shown above them).

Figure 1.1 shows the general energy distribution in the solar spectrum outside of the Earth's atmosphere (solid curve) and on the surface of the Earth on a clear day when the Sun is close to the zenith. The solar spectrum on the surface of the Earth is dotted with several absorption lines, which can be distinguished in the figure by the dark "valleys." /13

Brief information on the solar system planets discussed in this chapter is given in Table 1.1.

2. Earth

The Earth moves around the Sun along an orbit having the form of an ellipse, or more exactly, the center of gravity of the Earth-Moon system moves. The average distance of the Earth from the Sun is assumed to equal approximately $150 \cdot 10^6$ km, and the average velocity of the Earth along its orbit is about 30 km per second.

TABLE 1.1*

AVERAGED CHARACTERISTICS OF CERTAIN PLANETS OF THE SOLAR SYSTEM AND THE MOON [2]

Name	Earth	Venus	Mars	Moon
Mean distance from the Sun in A.U. (astronomical units)	1,000	0,723	1,524	1,000
Sidereal period (c — days)	365^{c},256	224^{c},70	687^{c},0	27^{c},32
Orbital velocity in km/sec	29,7	34,9	24,1	1,03
Equatorial diameter in km	12756,3	12260	6791	3477,02
Relative mass	1,000	0,814	0,1077	0,01229
Relative density (water — 1.0)	5,52	5,1	3,97	3,34
Force of gravity on surface	1,0	0,89	0,38	0,165
Rotational period around axis (c — days, h — hours, m — minutes)	23^{h}56^{м}	225^{c}	24^{h},6	27^{c},3
Maximum surface temperature in ° C	60	540	24	150
Gases in the atmosphere	Several	CO_2, H_2O	CO_2, H_2O	—
Albedo**	0,35	0,76	0,15	0,07

*Commas in the numbers indicate decimal points.

**Albedo (A) is the ratio of the radiant flux Φ scattered by an illuminated surface in all directions to the radiant flux Φ_0 falling on this surface, $A = \Phi/\Phi_0$.

The Earth makes a complete revolution around the Sun every 365.256 days. This is the so-called stellar or sidereal year.

The most important physical characteristic of the Earth is the acceleration of the force of gravity (in practical calculations, it is assumed to equal 981 cm/sec^2).

The air envelope of the Earth — the atmosphere — plays the role of a light filter, letting only solar radiation reach the Earth which has a wavelength from 0.29 to 2.4 microns [3].

The shortwave (hard) ultraviolet solar rays are held back by a layer of ozone located at altitudes above 20 kilometers, and the infrared rays are held back by water vapor and carbon dioxide which is present in the atmospheric air. As a result of this, the integral flux of solar radiation decreases by approximately 30% and is about 840 kcal/m^2·hr on the surface of the Earth.

Many models of the atmosphere have been published in different countries. In the USSR, a standard atmosphere is used (SA GOST 4401-64), a concise table for which is given in the Appendix (Table A.1).

In terms of altitude, the atmosphere of the Earth may be divided into the troposphere, stratosphere, mesosphere, thermosphere, and exosphere.

The troposphere is characterized by a gradual temperature decrease with an increase in altitude, and the gradient of the altitudinal change is approximately 6° C per 1 kilometer. It contains about 80% of the mass of the entire atmosphere, almost all water and suspended solid particles. Due to the nonuniform heating of the Earth's surface and the air adjacent to it, the upper boundary of the troposphere is higher at the equator than it is at the poles (in summer it rises, in winter it falls). The mean yearly altitude of the troposphere at the equator approximately equals 15 — 17 kilometers, at the poles — 7 — 8 kilometers, and at the middle latitudes — 11 kilometers [1]. Clouds and winds of differing force and direction may be observed in the troposphere.

The stratosphere extends approximately to an altitude of 50 — 60 kilometers. The majority of phenomena which are intrinsic to the troposphere are not observed in the stratosphere — for example, there are almost no clouds, and the winds have a constant direction and reach high velocities. There is a basic amount of atmospheric ozone in the stratosphere. The tropopause is located between the troposphere and the stratosphere. The upper boundary of the tropopause is not constant, and depends on the geographic latitude and time of year.

The mesosphere extends to an altitude of 80 kilometers. Its air temperature decreases with increase in altitude, and reaches a minimum. The mesosphere is separated from the stratosphere by a transitional layer, called the stratopause. There are still no unified opinions regarding the definition of the stratopause, but it is probably most correct to assume that the stratopause is a region of a temperature maximum at an altitude of about 50 kilometers.

The thermosphere is characterized by a rapid temperature /14
increase (Figure 1.2). It extends to an altitude of approximately 800 kilometers from the surface of the Earth. There is a comparatively thin layer between the mesosphere and the thermosphere with a constant minimum temperature on the order of -70° C, which is called the mesopause.

The exosphere, or the scattering sphere, is characterized by such a strong vacuum that the gas particles in this layer barely collide with each other, and the most rapid particles are even ejected from the field of the Earth's attraction and are carried into space. The exosphere extends up to 1100 — 1300 km. Interplanetary space begins above the exosphere.

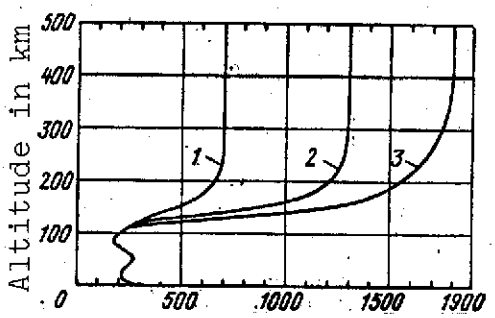

Figure 1.2. Daily altitudinal distribution of air temperature in the atmosphere of the Earth.

1 — minimum values (night); 2 — average values; 3 — maximum values (day).

Based on the electric characteristics, along the vertical profile the atmosphere may be divided into the neutrosphere and the ionosphere. This division is based on the distribution of electrically charged gas particles — ions — in the atmosphere. The lower part of the atmosphere extends approximately to an altitude of 60 km, and contains predominantly neutral particles which represent the neutrosphere. The ionosphere is located at altitudes greater than 60 km, and contains a great number of electrically charged particles, in contrast to the neutrosphere.

Atoms of atmospheric gases are ionized in the ionosphere, under the influence of ultraviolet, X-ray, and gamma radiation from the Sun. As a result of this, free electrons and ionized atoms and molecules occur.

The electron concentration reaches its maximum value at altitudes of 300 — 400 km.

The composition of the atmospheric air of the Earth up to altitudes on the order of 80 — 100 km is given in Table 1.2, whose data indicate a predominance of nitrogen and oxygen.

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*Due to the highly rarefied air in the thermosphere, the high temperatures characterize only the molecule velocity and not their thermal influence on the aircraft.

TABLE 1.2

COMPOSITION OF ATMOSPHERIC (DRY) AIR AT SEA LEVEL [6]

Gas	Chemical formula	Content by volume, %	Gas	Chemical formula	Content by volume, %
Nitrogen	N_2	78.09	Neon	Ne	$1.8 \cdot 10^{-3}$
Oxygen	O_2	20.95	Krypton	Kr	$1.14 \cdot 10^{-4}$
Argon	Ar	0.93	Xenon	Xe	$8.7 \cdot 10^{-5}$
Carbon dioxide	CO_2	0.03 (average)	Ozone	O_3	$1.0 \cdot 10^{-6}$
			Methane	NH_4	$1.5 \cdot 10^{-4}$
Hydrogen	H_2	$5.00 \cdot 10^{-5}$	Nitrous oxide	N_2O	$5.0 \cdot 10^{-5}$
Helium	He	$5.24 \cdot 10^{-4}$			100%

Among the gases comprising the atmospheric air, oxygen is of great importance for human activity. The properties of atmospheric air are given in the Appendix (see Table A.2). /15

In addition to the regular bi-atomic oxygen (O_2), the stratosphere also contains a small amount of ozone (O_3). Ozone is formed in the stratosphere under the influence of ultraviolet radiation of the Sun, when part of the oxygen molecules (O_2) is decomposed by atoms (O), and then a certain amount of three-atomic ozone molecules (O_3) are formed during the combination process.

Up to altitudes of approximately 60 km, atmospheric air includes ozone, and its maximum concentration occurs at altitudes of 25 — 35 km. Here the volumetric content of ozone is only 0.000005%. The total amount of ozone in the atmosphere may be characterized by the width of a layer formed by it if it were reduced to normal conditions (760 mm Hg at 0° C). The width of such an ozone layer on the average will be only 3 mm.

In spite of such an insignificant amount of ozone in the atmosphere, its importance is very great, since it absorbs the basic portion of shortwave ultraviolet rays of the Sun with a wavelength from 0.1 to 0.24 microns, which have a pronounced biological effect. If there were no ozone in the atmosphere, life on Earth would be impossible or it would acquire different forms.

Ozone is a strong oxidizer. It breaks down organic substances, provides dyes, and changes many materials (potassium, sodium, etc.) into oxides. Rubber hoses, which are used in oxygen systems, are decomposed after ozone with a concentration of 0.02 — 0.03 mG/l acts upon them. Plastics are stable toward ozone, and also certain types of rubbers (chloroprene, silicon, etc.).

The dissociation of oxygen and nitrogen molecules takes place above the mesopause, and practically all of the molecular oxygen is changed into atomic oxygen at an altitude of approximately 175 km. It is much more difficult to dissociate nitrogen, and even at great altitudes a certain portion of it remains in the molecular state.

Carbon dioxide is not distributed uniformly in the atmosphere, and it is present in large amounts in the air above mountains and industrial regions. Measurements have shown that the total amount of carbon dioxide in the atmosphere gradually increases when a large amount of fuel is being burned.

3. Radiation Conditions in Circumterrestrial Space

Ionizing (penetrating) radiation designates fluxes of shortwave electromagnetic radiation (X-ray and gamma rays) and elementary particles formed during intranuclear reactions

— alpha particles (naked nuclei of helium), beta particles (electrons and positrons, protons and neutrons).

The wavelength characteristics of radiation are given below [22].

Type of radiation	Wavelength nm	Type of radiation	Wavelength nm
Infrared rays	$75 \cdot 10^4$ — 760	X-rays	
Visible rays	760 — 400	soft	0.6 — 0.2
Ultraviolet rays		average hardness	0.2 — 0.1
Near	400 — 10	hard	0.1 — 0.05
Far	10 — 5	Gamma rays	0.004

The energy of elementary particles is usually measured in electronvolts (eV)*.

*Arbitrary units of an electronvolt (eV) are usually used in practice: kiloelectronvolt (keV) = 1000 eV; megaelectronvolt (MeV = $1 \cdot 10^6$ eV; and billionelectronvolts (BeV) = $1 \cdot 10^9$ eV.

An electronvolt is the energy which a particle acquires /16 having one elementary electrical charge (electron charge), when moving in an electric field between points with differing potentials in 1 V:

$$1 \text{ eV} = 1.60207 \cdot 10^{-19} \text{J} = 1.6 \cdot 10^{-12} \text{ erg}.$$

Ionizing radiation can penetrate bodies and materials (it is thus called penetrating radiation), and ionizes them to a considerable extent.

The intensity of ionizing radiation is characterized by the mean free path of a particle in matter, or by the mass of absorbing material (g/cm^2), per unit of its surface, at which the particle energy is completely absorbed.

No threat to human life is posed on the surface of the Earth by ionizing radiation, both of a solar and terrestrial origin (terrestrial radiation is small, and the atmosphere and the magnetic field of the Earth provide reliable protection from the action of the most active solar ionizing radiation).

The crew of an aircraft no longer has this protection outside of the atmosphere and the radiation belts of the Earth, and the influence of ionizing radiation, as a dangerous flight factor, is a very important factor.

Alpha particles (α-particles) have the greatest specific ionization. Under normal physical conditions, one alpha particle in the air produces on the average 30 pairs of ions.

The penetrating ability of α-particles is small. They are completely absorbed by sheets of paper and aluminum foil, and they cannot penetrate an ordinary jacket. In living tissues, α-particles penetrate to a depth up to 0.05 mm (Figure 1.3).

Beta rays (β-particles) represent a flux of electrons whose mean free path depends on their energy. Although the penetrating ability of β-particles is much greater than that of α-particles, it is also very small. Thus, β-particles are strongly attenuated by the jacket of a man, and are practically completely absorbed by metallic screens with a thickness of several millimeters (for example, for Al — approximately 5 mm, Pb — from 0.3 to 1.0 mm). In living tissues, β-particles penetrate to several millimeters.

Gamma rays (γ-rays) are a component of solar radiation, whose intensity greatly increases during solar flares. This radiation is produced under the action of various types of penetrating radiation with matter (including tissues of a living organism).

The penetrating ability of γ-rays is very great. For example, a layer of aluminum 8 cm thick is necessary to attenuate the energy of this radiation per 1 MeV by a factor of four.

Protons (p) are positively charged nuclei of hydrogen, and represent a large portion of primary cosmic radiation and solar corpuscular radiation. They are also a basic component of penetrating radiation in the inner radiation belt of the Earth (Figure 1.4).

Their penetrating ability is greater than that of α-particles, and less than that of β-particles (see Figure 1.3), but the interaction of protons with matter, particularly with living tissues, is much greater and more complex.

Neutrons (n) are neutral particles produced as a result of the interaction of protons with atoms in the atmospheric air, and they are also produced in large amounts in atomic reactors.

In the free state, neutrons exist for a comparatively short time (14.5 minutes), decomposing into protons and electrons ($n \rightarrow p + e$). Not having a charge, they barely interact with electrons of atoms and produce very weak ionization.

The nuclei of light elements (He, Li, Be, C) exist in comparatively small amounts in primary cosmic radiation. There is still no unified viewpoint regarding their penetrating ability and interaction with different materials. /18

The ionizing action of X-rays and γ-rays is characterized by their dose which is measured in roentgens (R),* and that of

*The milliroentgens (mR = $1 \cdot 10^{-3}$ R), and the microroentgens (μR = $1 \cdot 10^{-6}$ R) are fractional units of the roentgen.

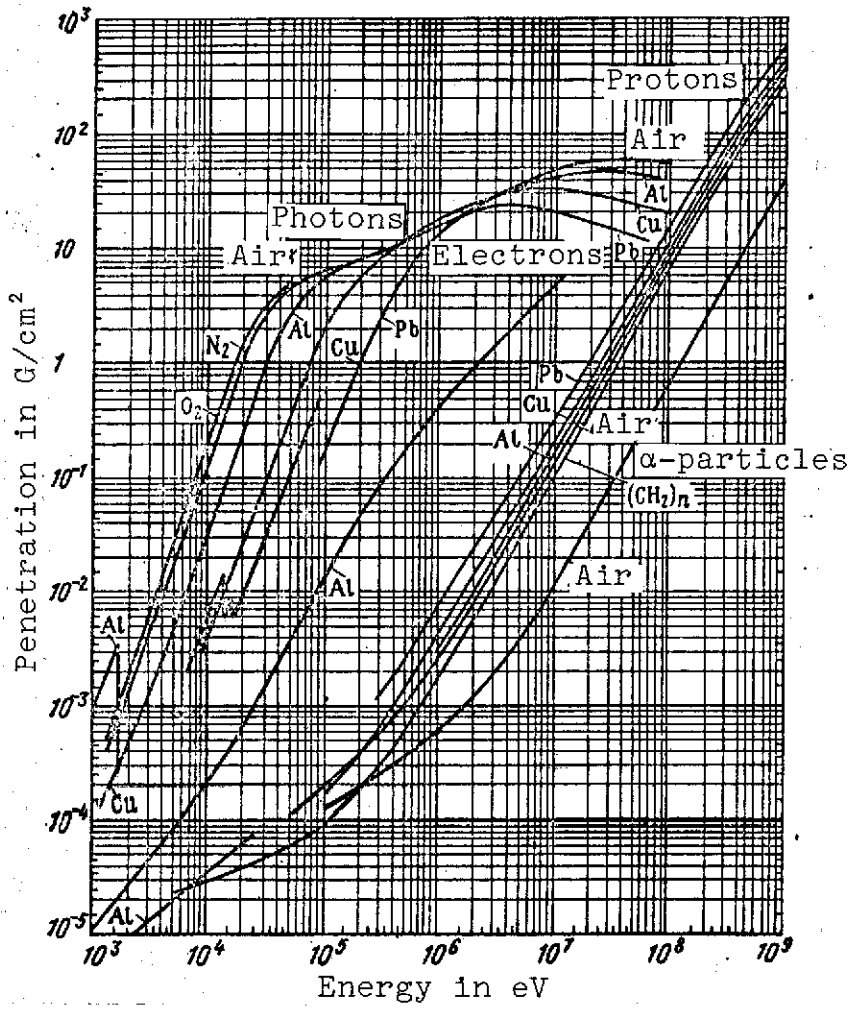

Figure 1.3. Dependence of the mean free path of penetrating radiation particles on their energy.

the remaining types of radiation is measured in rads (GOST 8848-63).*

A dose of ionizing radiation per unit time is called the strength of the radiation dose.

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*The millirad (mrad = $1 \cdot 10^{-3}$ rad) and the microrad (μrad = $1 \cdot 10^{-6}$ rad) are fractional units of the rad.

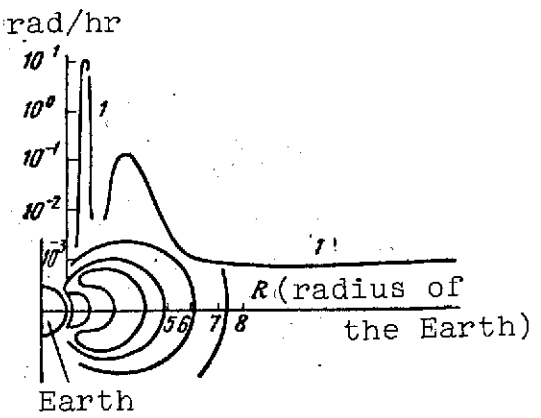

Figure 1.4. Change in radiation level (1) behind shielding of 2-3 G/cm^2 with radial departure from the Earth in the plane of the geomagnetic equator.

The strength of the radiation dose is measured in R/sec, R/hour, mR/sec, etc.

The biological action of ionizing radiation on living tissues is determined by the amount of energy absorbed by them (i.e., the absorption dose in rads), the specific density of the ionization produced by ionizing radiation, the strength of the dose, the temperature, and the acidity of their radiated tissue.

The biological influence of different types of penetrating radiation is compared in terms of their relative biological effectiveness (RBE), for which a special unit of measurement is assumed — the biological equivalent of the rad (Rem). One RBE designates that dose of any type of ionizing radiation which is absorbed by a living tissue and which causes the same biological effect as one rad of X-rays or γ-rays.

It is apparent that the absorbed doses of different forms of radiation, expressed by an identical number of Rem, will be identical in terms of their biological effect.

The absorbed dose of radiation, expressed in rads R_{rad} and the biological dose expressed in Rems (R_{Rem}), are related by the following equation:

$$R_{Rem} = R_{rad} \cdot RBE \qquad (1.2)$$

where RBE is the relative biological effectiveness which depends on the nature of the radiation of the biological process being examined, the magnitude, and the strength of the dose.

The following values of radiation RBE are used in calculations for different types of radiation:

X-rays and γ-rays	1
β-particles	1
α-particles and protons	10
rapid neutrons	10
slow (thermal) neutrons	5

Thus, for β-particles and γ-rays, 1 Rem = 1 rad, and for α-particles and protons, 1 Rem = 0.1 rad.

Primary cosmic radiation (PCR), radiation in the radiation belts of the Earth, and radiation connected with flares on the Sun are encountered outside of the atmosphere.

Primary cosmic rays represent a flux of charged particles consisting primarily of protons (approximately 85%), α-particles (approximately 14%), and the nuclei of light elements (about 1%), coming from space with energies of several megaelectronvolts up to 10^{12} eV.

Omnidirectionality and constant intensity in time are characteristics of PCR.

Particles whose energy reaches colossal amounts — 10^{19} eV and apparently even 10^{20} eV — are encountered in cosmic rays, although very rarely. This is a billion times /19

greater than that produced by even the most powerful contemporary particle accelerators.

However, although the energy of the remaining particles of cosmic rays is very great, the amount of particles in the total PCR flux per one second is 1.8 — 4 per 1 cm^2.

Interacting with the atmosphere of the Earth, at altitudes of 35 — 40 km, these particles produce secondary cosmic radiation consisting of mesons, neutrons, protons, and the softer components — electrons, and also γ-quanta and other particles [8].

In the absence of a shielding, the total dose from PCR is 22 mrad/day or 130 mRem/day. This value is usually increased by 50 — 100% in calculations of the contribution made by PCR to the total dose of radiation absorbed by the human body [9].

Close to the Earth, the total PCR dose is much less due to the screening action of the magnetic field. Thus, on an orbit located at an altitude of 200 — 600 km and inclined to the equatorial plane by an angle of 65°, the PCR dose is 8 — 10 mrad/day, with allowance for secondary radiation [9]. The penetrating ability of PCR is unusually great. For example, a layer of lead 20 cm thick or greater is necessary to reduce it by half. Due to the impossibility of producing such a screen, the dose from PCR within a spacecraft will be practically the same as outside of it, i.e., in open space.

As a result of experimental studies performed by Soviet and American scientists on artificial Earth satellites (AES), it has been established that there is an enormous region saturated with charged particles having a very high energy around

the Earth. These particles do not reach the surface of the Earth, falling into its "magnetic trap."

The region of saturation with charged particles is arbitrarily divided into the inner, outer, and "outermost" radiation belts. In actuality, there is no clearly expressed boundary between them.

The inner radiation belt begins at an altitude of 500 to 1500 km and extends to an altitude of about 10,000 km from the surface of the Earth, with a maximum of its saturation with particles at an altitude of about 3500 km. This belt is formed by rapid protons with energies on the order of tens and hundreds of megaelectronvolts and electrons with energies on the order of tens and hundreds of kiloelectronvolts.

Protons represent the greatest radiation danger in this belt. The average biological strength of the dose produced by protons on a section of an AES orbit passing through the inner radiation belt, behind a screening layer of 1 G/cm^2, is approximately 5 Rem per hour. Electrons of the inner belt will constantly be absorbed by this screen, and the strength of the bremsstrahlung thus produced will not exceed 0.1 Rem per hour [5]. Therefore, remaining briefly (10 — 15 minutes) in the inner radiation belt of the Earth does not represent any great danger for spacecraft crews.

The outer radiation belt is located at a distance of 10,000 to 50,000 km from the surface of the Earth, with an intensity maximum at an altitude of 15,000 — 20,000 km. This belt consists primarily of electrons having energies from 20 keV to several megaelectronvolts. In this belt, it is not the electrons themselves (β-particles) which represent a radiation

danger, but the γ radiation and X-ray radiation produced by them when passing through matter. If the screening layer is less than 2 — 3 G/cm^2, the human body will receive a comparatively large radiation dose — 40 rad/day [9].

The outermost radiation belt is believed to have been produced by several high altitude nuclear explosions (for example, on July 9, 1962, the USA carried out the operation "Starfish"), and it consists of electrons with energies up to 7 MeV.

Solar corpuscular radiation primarily consists of protons and α-particles. With a shielding of more than 3 — 5 G/cm^2, the influence of α-particles will be very small. During solar flares, the flux of protons contains particles with an energy of several megaelectronvolts up to tens of billion electronvolts [9]. /20

The dose of radiation produced by protons during solar flares fluctuates very widely. It is assumed that the integral dose of proton radiation will not exceed 100 Rem behind a shielding on the order of 13 G/cm^2, during solar flares such as those of February, 1956; 15 G/cm^2, during solar flares such as May, 1959, and 2 G/cm^2 — during solar flares such as August 1958 [5].

There are opinions maintaining that the danger from radiation may be reduced by correctly selecting the flight trajectory (above or below the radiation belts of the Earth), and also by organizing a reliable system of predicting solar flares and providing advance information about them to the spacecraft crews.

The use on the spacecraft of a powerful radiation-safe covering, the construction of special radiation shelters, and the administration of medical-pharmacological agents are no less important as protective measures.

4. Moon

The Moon moves along a trajectory having the form of an ellipse, at whose focal point the Earth is located. At perigee, the minimum distance between the Moon and the Earth is 363,300 km, and at apogee — 405,500 km.

On the average, the distance from the Moon to the Earth is assumed to equal 380,000 km.

Since the mass of the Moon is much less than the mass of the Earth, the acceleration of gravity on the surface of the Moon equals 1.61 m/sec^2. This is why any body on the Moon (including a space suit) is six times lighter than on the Earth.

The surface layer of the Moon was formed over several million years under conditions of sharp temperature fluctuations, no gravitation, and a high vacuum. Bombardment by meteors and cosmic and solar penetrating radiation had a great influence on the formation of this layer.

Analyses of samples of soil collected by the automatic station "Luna-16" have shown that the surface layer of the Moon resembles a very friable substance, which is not dust, and whose structure resembles pumice.

This layer is not uniform. Along with extremely small particles measuring 70 — 100 microns, it also contains larger particles with dimensions ranging from centimeters to tens of centimeters.

There is an intermediate layer under the thin surface layer of the Moon, which gradually changes into a denser, rock base. The intermediate layer apparently determines the "supporting" capacity of the lunar soil.

Table 1.3 gives data on the structure of the lunar soil in the region where the Soviet automatic station "Luna-16" landed.

On the average, the lunar soil only reflects about 7% of the light falling upon it. This means that it is covered by material which is very dark, since dry chernozem and the dark rocks on the Earth are characterized by similar albedo values.

The lunar day lasts 14.76 Earth days. During this time, the lunar surface turned toward the Sun is intensely heated. It is well known that, when the Sun is at the zenith of the Moon, its surface temperature reaches 150° C, and during the two-week lunar night, it falls to -150° C.

The Moon has practically no atmosphere, and therefore it contains no wind, clouds, fog, rain, snow, etc.

The strength of the magnetic field of the Moon is approxi- /21
mately four hundred times less than the strength of the magnetic field of the Earth [11]. Due to the absence of an atmosphere and a magnetic field, the surface of the Moon is primarily irradiated by those fluxes of penetrating radiation which exist in free interplanetary space.

TABLE 1.3*

DATA ON THE STRUCTURE OF THE LUNAR SOIL IN THE REGION OF THE "LUNA-16" LANDING**

Layer properties	Surface layer	Intermediate layer	Rock base
Thickness in meters	0,0—0,15	0,15—0,35	—
Specific weight in G/cm^3	0,5—0,8	0,8—1,2	2,6—3,3
Porosity in %	90—80	60—50	10—0,05
Crushing strength in kG/cm^2	0,1	10	600—2500

*Commas in the numbers indicate decimal points.

**A. P. Vinogradov. Preliminary Results of Research on the Lunar Soil. Izvestiya, October 29, 1970.

Due to its screening action, the PCR intensity on the lunar surace is one-half its value in free space and is about 50 — 130 mRem/day [10].

The PCR is supplemented by the natural radioactivity of rocks on the lunar surface and the induced radioactivity arising under the influence of PCR and radiation of the Sun. The strength of the radiation dose from this radioactivity does not exceed $6 \cdot 10^{-5}$ Rem/hr [10]. Solar ionizing radiation produced during flares represents the greatest danger on the surface of the Moon, since the radiation dose produced by these flares, depending on the strength of the flare, may exceed several hundreds of Rem [10].

The illumination on the lunar surface is characterized by the following data:

Maximum illumination with solar light	140,000 lux
Illumination with solar light reflected from the "full" Earth	30 lux
Illumination from stellar light	0.0005 lux

Due to the diameter of the Moon, which is comparatively small as compared with the Earth, the theoretical visibility upon it is almost half that it is on the Earth. For example, in the absence of atmospheric refraction when the eyes of an observer are raised 2 m (h) above the surface of the Moon, the visibility is determined by the following formula

$$L \approx 1.89\sqrt{h} \approx 2.63 \text{ км}.$$

With such poor visibility, great difficulties arise both in visual observations on the Moon and in radio communication.

5. Mars and Venus

Mars is much smaller in size than the Earth, and the force of gravity on it is almost three times less than it is on the Earth.

A year on Mars is almost twice as great as on the Earth. However, a day is almost just as long as on the Earth (see Table 1.1).

Photographs taken by the American spacecraft "Mariner-4" /22 provide a basis for assuming that the surface of Mars, just like the surface of the Moon, is covered with craters, probably of a meteorite origin.

It is assumed that the dark spots on the surface of Mars represent outcroppings of basic rocks, and the light regions represent matter which has been formed from the breakdown of the basic rocks. Since it is 1.5 times farther from the Sun than is the Earth, Mars receives 2.25 times less solar heat and light than does the Earth. The climate on Mars is therefore much harsher than on the Earth.

Atmospheric pressure on the surface of Mars is about 4 mm Hg. The atmosphere of Mars includes carbon dioxide and water vapor. At noon in the equatorial belt of Mars, the temperature of the upper layer of the soil surface may reach 30° C, but when the Sun sets, it drops far below zero, and in the morning reaches -40° C. The temperature at the poles of Mars is very low (approximately -70° C) [11].

Measurements performed by the American spacecraft "Mariner-4" revealed that Mars has an insignificant magnetic field (in any case, $3 \cdot 10^{-4}$ times weaker than the magnetic field of Earth). It has also been found that there are practically no radiation belts on Mars [11].

Mars is most similar to the Earth in the periods of its opposition, rotating every 780 days.

Every 15 — 17 years (for example, 1956, 1971, etc.) the so-called "great oppositions" are repeated, when Mars approaches the Earth to the closest distance of 56,000,000 km.

Venus is more similar to the Earth than all the other planets in terms of its size and mass (see Table 1.2). It has a dense atmosphere and is constantly covered by a thick layer of clouds which cover its surface. The force of gravity on

Venus is almost the same as on the Earth. Venus is located closer to the Sun than is the Earth. Therefore, it receives 2-1/2 times more heat and light than does the Earth. When Venus and the Earth move around the Sun, the distance between the planets changes from 40 to 260,000,000 km [2].

Measurements performed by the Soviet interplanetary station "Venera-4" confirmed existing opinions regarding the absence of radiation belts and a magnetic field on Venus. It is thus assumed that the concentration of charged particles in the upper atmosphere of Venus (at altitudes greater than 100 km) is at least two orders of magnitude less than the maximum concentration of charged particles in the ionosophere of the Earth [2].

The flight of "Venera-4" also corroborated the assumption that the atmosphere of Venus contains carbon dioxide (90%) and small amounts of nitrogen ($\leq$2%), oxygen ($\leq$0.1%), and water. Based on these data, the atmospheric pressure on the surface of the planet is 70 — 90 kG/cm^2 [11].

It is assumed that the temperature on the day and night sides of the surface of Venus is approximately the same — about 470° C [2].

Venus rotates in a direction which is opposite that of all the other planets, and almost always one of its sides is turned toward the Earth. Therefore, only a portion of its other side may be seen from the Earth, and then only when both planets are at specific positions.

6. Meteor Bodies and the Interplanetary Medium

Meteor Bodies. It has been established that a large number of very large and small solid bodies, which are called meteor bodies move in the interplanetary space of the solar system.*

Meteor bodies have very different dimensions — from large lumps to extremely small particles and cosmic dust.

It is assumed that meteor bodies are formed both during volcanic eruptions on planets in the solar system and their satellites, and are due to the gradual decomposition of volcanic /23 matter and small celestial bodies — comets and asteroids.

It is difficult to observe meteor bodies which are moving in interplanetary space from the Earth, since they reflect too small an amount of solar light. About 99% of these bodies move along elliptical and parabolic orbits, primarily in the same direction as the rotation of the Sun and the rotation of planets

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*The following terminology was proposed at the meeting of the International Astronomical Union in 1961.

Meteor is a light phenomenon which occurs when a particle from interplanetary space enters the atmosphere.

Meteor body is a certain object moving in interplanetary space.

Meteorite is a meteor body which reaches the surface of the Earth.

Micrometeorite is a meteorite whose diameter is much less than a millimeter, but is not less than several micrometers.

Meteor dust is particles with dimensions less than micrometeorites.

around the Sun takes place, with an average solar velocity on the order of 40 km/sec* (in the region of the Earth's orbit).

Based on their chemical composition, meteor bodies may be divided into stony, iron, and iron-stony. The chemical composition of stony meteor bodies is similar to the composition of terrestrial rocks. The specific weight of stony meteor bodies ranges from 0.5 to 3 G/cm^3, and that of iron meteor bodies ranges from 0.5 to 7.8 G/cm^3. Stony meteor bodies are observed much more frequently than are iron ones (10:1). Iron-stony meteor bodies comprise about 2%.

Entering the Earth's atmosphere at high velocities, meteor bodies are heated from friction with the air, become hot, break up, melt, and burn up at altitudes on the order of 70 — 30 km, forming a very bright light trail, the so-called falling stars. Only in very rare cases at comparatively small velocities and large masses do meteor bodies reach the Earth's surface in the form of meteorites and their fragments.

Particles of micrometeorites with dimensions up to 30 microns and meteor dust pass through the atmosphere and reach the surface of the Earth.

Up to the present, there have been no recorded cases of serious damage to AES and spacecraft as a result of their collision with meteor bodies. However, it is apparent that meteor bodies and particles may represent a real danger for spacecraft and space suits during prolonged flights in interplanetary space.

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*The average velocity of meteor bodies with respect to the Earth on a terrestrial orbit is the algebraic sum of their velocity with respect to the Sun and the velocity of the Earth with respect to the Sun (~30 km/sec).

In the general case, this danger may be as follows:

(a) Direct damage to the spacecraft hull and the vitally important parts of a space suit;

(b) Erosion of the optical devices (turbidity of the glass), elements of the solar batteries, and also the fabric coverings of the space suits (increase of permeability to gas);

(c) Harmful influence of meteor bodies passing through the screening layers upon the human body.

The problem of the dimensions and distribution of meteor bodies in interplanetary space is of great interest in this connection.

We may distinguish between individual *sporadic meteor bodies*, which are almost uniformly distributed in interplanetary space, and groups of these bodies — *meteor streams*.

It has been established by numerous observations and theoretical studies that the greater the mass of meteor bodies the less frequently they are encountered in interplanetary space.

Figure 1.5 shows a graph of the distribution of the average amount of sporadic meteor bodies in terms of their mass in circumterrestrial space, which is based on results of the flights of artificial Earth satellites, space rockets, and interplanetary stations.

The influence of meteorite particles with a weight of less than $1 \cdot 10^{-7}$ G may be reduced basically to erosion which is similar to the action of particles weighing on the order of $1 \cdot 10^{-6}$ to $1 \cdot 10^{-4}$ G and more [3].

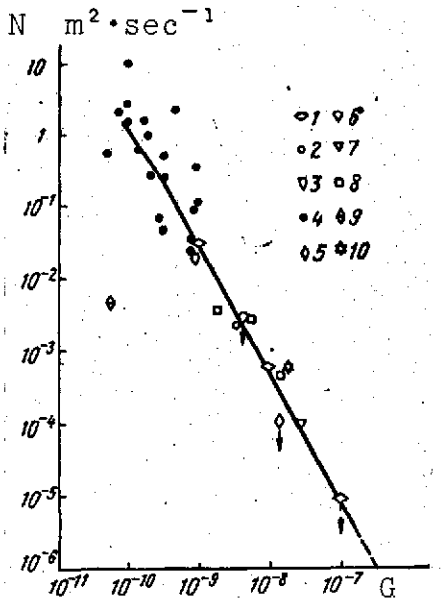

Figure 1.5. Approximate distribution of average number of sporadic meteor bodies in the vicinity of the Earth.

1 — "Explorer-8"; 2 — "Vanguard-3"; 3 — Explorer-1"; 4 — U.S. rockets; 5 — third USSR satellite; 6 — first USSR space rocket; 7 — second USSR space rocket; 8 — USSR automatic interplanetary station; 9 — "Pioneer-1"; 10 — USSR "Ekektron-2" (N — average number of collisions with an area of 1 $m^2 \cdot sec^{-1}$; G — particle weight).

Table 1.4 gives data on the probable average number of impacts in an area of 1 m^2 of sporadic meteor particles in interplanetary space, calculated from the graph in Figure 1.5 [4].

The following equation may be used to establish the distribution of meteor matter in circumterrestrial space*

$$N = \alpha m^{\beta}, \qquad (1.3)$$

where N is the total amount of meteor matter with a mass of m and more, which intersects a unit area per unit of time; α and β — constants determined experimentally.

For single (sporadic) meteor bodies $\alpha = 4.7 \times 10^{-15}$ particle per $m^2 \cdot sec$; $\beta = -1.34$. /24

In accordance with the model assumed, the average velocity and specific weight of meteor bodies approximately equal 30 km/sec and 0.5 G/cm^3.

Meteor streams which are formed due to the gradual breakdown of comets and other small celestial bodies move along the orbits of these bodies. When these orbits intersect the Earth as it moves around the Sun, there is a massive fall of meteors ("meteor streams").

*AIAA Paper, No. 366, 1969.

TABLE 1.4

PROBABLE AVERAGE NUMBER OF IMPACTS OF SPORADIC METEOR PARTICLES IN AN AREA OF 1 m^2 IN ONE SECOND IN INTERPLANETARY SPACE [4]

Particle weight in G	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
N_{av} in $m^2 \cdot sec^{-1}$	10^{-17}	10^{-16}	$3 \cdot 10^{-15}$	10^{-13}	10^{-12}	$5 \cdot 10^{-11}$	$8 \cdot 10^{-10}$	$3 \cdot 10^{-8}$	$5 \cdot 10^{-7}$	10^{-5}	$7 \cdot 10^{-4}$	$4 \cdot 10^{-2}$

Data on the basic meteor streams observed from the Earth are given in Table 1.5.

It follows from this table that:

— Meteor streams may be observed (each) from one to forty or more days, and the occurrence of some of them coincides in time;

— Meteor streams are not distributed uniformly over a year (most of them occur in August and December, and the fewest number appear in February, March, and May);

— The maximum number of possible encounters with meteor bodies in meteor streams may exceed by several factors the possible number of encounters with sporadic meteor bodies.

Consequently, a determination of the possible damage to spacecraft by meteor bodies cannot be based only on data regarding sporadic meteor bodies, but the possibility of its increase due to the action of meteor streams must be taken into account.

TABLE 1.5

DATA ON MAIN METEOR STREAMS OBSERVED FROM EARTH [3]

Stream	Date of maximum	Time intervals	Coordinates: Righy ascension, α	Coordinates: Declination, δ	Velocity, km/sec
Quadrantids	Jan. 3	Jan. 1-4	230°	+48°	42,7
Virginids	March 13	March 5-21	183	+4	30,8
Lyrids	April 21	April 20-23	270	+33	48,4
η-Aquarids	May 4	May 2-6	336	+0	64
Diurnal Arietids	June 8	May 29 - June 18	44	+23	39
Diurnal ζ-Perseids	9	June 1-16	62	+23	29
Sagittarids	11		304	−35	
Diurnal β-Taurids	30	June 24 - July 6	86	+19	32
Phoenicids	July 14		32	−48	
Southern δ-Aquarids	30	July 21 - Aug. 15	339	−17	43,0
Northern δ-Aquarids		July 14 - Aug. 19	339	−5	42,3
Southern ι-Aquarids		July 16 - Aug. 25	338	−14	35,8
Northern ι-Aquarids		July 16 - Aug. 25	331	−5	31,2
α-Capricornids	Aug. 1	July 17 - Aug. 21	309	−10	25,5
Perseids	12	July 29 - Aug. 17	46	+58	60,4
κ-cygnids		Aug. 19-22	289	+56	26,6
Draconids	Oct. 10	Oct. 10	264	+54	23,1
Orionids	22	Oct. 18-26	94	+16	66,5
Southern Taurids	Nov. 1	Sept. 15-- Dec. 15	51	+14	30,2
Northern Taurids	10	Oct. 17 - Dec. 2	52	+21	31,3
Andromedids	7	Nov. 7	22	+27	21,3
Leonids	17	Nov. 14-20	152	+22	72,0
Puppids/Velaids	Dec. 6	Dec. 1-9	140	−50	
Geminids	14	Dec. 7-15	113	+32	36,5
χ-Orionids		Dec. 9-14	87	+21	30,6
Monocerotids		Dec. 13-15	103	+8	44,0
Ursids	22	Dec. 17-24	206	+80	35,2

In interplanetary space beyond the boundaries of the Earth's orbit, there are no doubt many meteor streams which are still unknown. One of these was encountered by the Soviet interplanetary station "Mars-1" at a distance of 20 — 40 million kilometers from the Earth (1963).

To estimate the meteor danger on the surface of the Moon, at the present time it is possible to use the same data as for circumterrestrial interplanetary space.

In a quantitative estimate of meteor danger, in addition to data on the average number of impacts of meteor particles per unit time and per unit surface, it is necessary to take into account the length of time in interplanetary space (and on the surface of the Moon), the probability of meteor particles with a certain mass entering the spacecraft or a space suit, and the law governing the distribution of this probability. /25

The interplanetary medium has been studied systematically only during the last few years, and as of the present there is not sufficient data to establish its physical properties.

However, the data obtained indicate that the interplanetary medium should be regarded as a certain plasma. It is assumed that the interplanetary gas pressure within the solar system is $1 \cdot 10^{-13}$ mm Hg.

It is assumed that in galactic space the pressure of the medium equals $1 \cdot 10^{-16}$ mm Hg [1].

REFERENCES

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1. Brand, D. J. and P. A. Khodzh. Astrofizika solnechnoy sistemy (Astrophysics of the Solar System), Moscow, "Mir" Press, 1967.

2. Uippl, F. Zemlya, Luna i planety solnechnoy sistemy (Earth, Moon, and Planets of the Solar System). Moscow, Nauka Press, 1967.

3. Okolozemnoye kosmicheskoy prostranstvo. Spravochnyye dannyye (Circumterrestrial Space. Reference Data). Edited by F. S. Johnson. Moscow, "Mir" Press, 1966.

4. Space Research. Trudy vsesoyuznoy konferentsii (Transactions of the All-Union Conference). Moscow, Nauka Press, 1965.

5. Antipov, V. V., M. D. Nikitin, and P. P. Saksonov. On the Earth-Moon Trajectory. Priroda, No. 4, 1965.

6. Martov, B. A. Gazovyy sostav atmosfery i metody yego analiza (Gas Composition of the Atmosphere and Methods of Analyzing It). Moscow, Izdatel'stvo AN SSSR, 1961.

7. Gurshteyn, A. A. Surface Layer of the Moon. Priroda, No. 6, 1967.

8. Kozlov, V. F. and Yu. S. Troshkin. Spravochnik po radiatsionnoy bezopasnosti (Handbook on Radiation Safety), Moscow, Atomizdat, 1967.

9. Grigor'yev, Yu. G., Ye. Ye. Kovalev, and A. V. Lebedinskiy. Criteria for Radiation Safety of Long Space Flights. Problemy kosmicheskoy biologii (Problems of Space Biology), Moscow, Nauka Press, Vol. VI, 1967.

10. Vikhrov, A. N., V. Ye. Dudkin, Ye. Ye. Kovalev, and L. N. Smirennyy. Determination of Radiation Conditions on the Lunar Surface. Voprosy dozimetrii i zashchity ot izluchenly (Problems of Dosimetry and Shielding from Radiation), Moscow, Atomizdat, No. 6, 1967.

11. Kroshkin, M. G. Fiziko-tekhnicheskiye osnovy kosmicheskikh issledovaniy (Physico-Technical Bases of Space Research), Moscow, Mashinostroyeniye, 1969.

CHAPTER 2
PHYSICAL FACTORS ASSOCIATED WITH FLIGHTS AND THEIR INFLUENCE ON THE HUMAN BODY

During flights, humans are subjected to the influence of /27
differing factors caused both by the properties of the medium surrounding them, and by mechanical influences arising during the flight. These include, for example, temperature, humidity, and composition of gases in the medium surrounding man, mechanical overloads, vibrations, penetrating radiation, etc.

Let us examine these factors and their influence on man.

1. Influence of Physical Factors on the Breathing Process

The human respiratory organs, which carry out the processes of gas exchange (basically oxygen and carbon dioxide) between the human body and the inhaled air, include the respiratory tracts (nose and nose-throat, larynx, trachea, and bronchus) and the lungs (Figure 2.1).

Within the lungs, the bronchus, which repeatedly split up into the very smallest ramuli, terminate with alveoli pulmonis with a diameter of about 0.2 mm — alveoli which are closely intertwined with the blood vessels. Diffuse gas exchange takes place in the alveoli, during which oxygen from the alveolar air, which fills the alveoli, changes into blood for supplying the human tissues, and the carbon dioxide which is liberated by the body — into alveolar air. The total surface of the aveoli in

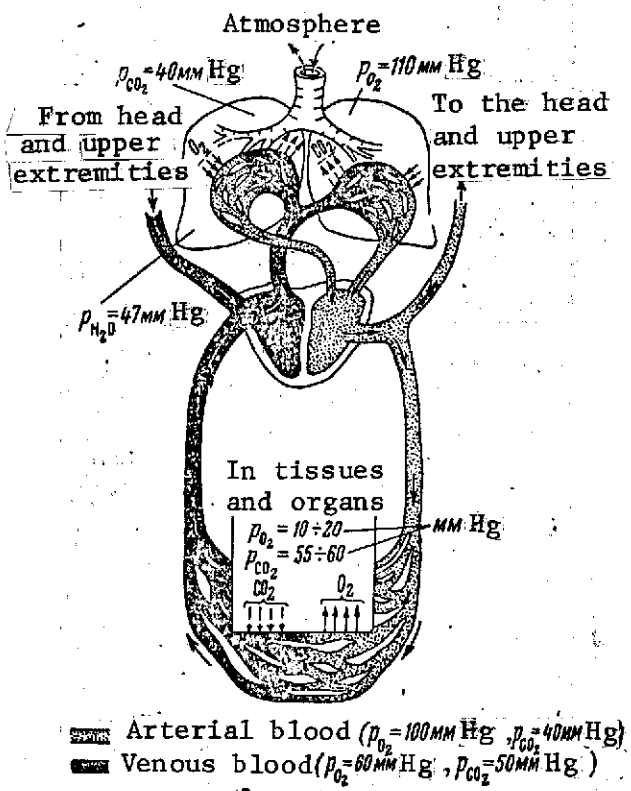

Figure 2.1. Diagram of circulation and gas exchange in the human body.

the lungs is 90 — 120 m^2. The human respiration rate is not constant, and depends on the state of the body and its activity. Thus, in a state of rest, the human respiration rate is 12 — 15 breaths (inhale — exhale) per minute, but during physical work it is up to 20 — 25 breaths per minute.

In a state of rest, with each inspiration and expiration about 0.5 liters of air enters the lungs. This amount of air is called *the respiratory air*, or the inspiration-expiration volume. During work, the volume of inspiration-expiration may increase to 1.5 — 1.8 liters.

Following the human inspiration and expiration at rest, with an increase in the load on the respiratory muscles on the average 1.5 liters of air may be introduced or withdrawn from the lungs in addition. This additional air is called *supplementary air* during inspiration and *reserve air* during expiration. The maximum amount of air, which humans may expire after very deep inspiration, is called the *vital capacity of the lungs*. The vital capacity of the lungs fluctuates between 2 — 6 liters. After very deep expiration, the lungs still contain about 1.5 liters of air — this is *residual air*. Consequently, the greatest amount of air which may be found in the lungs equals the sum of the vital capacity and the residual air. /28

The concept of pulmonary ventilation is used for the characteristic of respiration — the total amount of air passing through the lungs during inspiration-expiration, referred to unit time.

Consequently, the pulmonary ventilation

$$Q_p = nV \qquad (2.1)$$

where n is the respiration rate per one minute; V — inspiration-expiration volume in liters.

The pulmonary ventilation in a state of human rest is about six liters per minute, and it may increase up to sixty and more liters per minute during a physical load, depending on its magnitude. The pulmonary ventilation may be also increased during high altitude flights, depending on the emotional state of the pilot and other factors.

As has already been noted, during respiration gas exchange in the lungs does not occur directly with the atmospheric inspired air, but with the alveolar air, which differs greatly from the atmospheric air in terms of its composition (Table 2.1).

It has been established that the volumetric composition of components in atmospheric air remains approximately the same up to altitudes of 80 — 100 km. Out of all the respiration components, oxygen is very important, not its volumetric content in the air, but its partial pressure.

With an increase in altitude, the partial pressure of oxygen in atmospheric air p_{O_2} decreases according to the Dalton law:

TABLE 2.1

AVERAGE DATA ON COMPOSITION, PRESSURE, AND VOLUMETRIC CONTENT OF DIFFERENT GASES IN AIR USED FOR HUMAN RESPIRATION (AT AN ATMOSPHERIC PRESSURE OF 760 mm Hg) [2]

Type of air	O_2		CO_2		N_2		Water vapor	
	Pressure mm Hg	Volume %	Pressure mm Hg	Volume %	Pressure mm Hg	Volume %	Pressure mm Hg	Volume %
Atmospheric	159	20.95	0.20	0.03	594.8	78.22	6*	0.8
Expired	119	15.70	27	3.80	584	77.1	30	3.9
Alveolar	100	14.00	40	5.60	573	74.2	47	6.2

*This corresponds to a humidity of 40% and 18° C.

$$p_{O_2} = \frac{\xi_{O_2} p_H}{100}, \qquad (2.2)$$

where p_{O_2} is the oxygen partial pressure in mm Hg; ξ_{O_2} — volumetric content of oxygen in air, ξ_{O_2} = 21% = const; and p_H — atmospheric pressure at the altitude considered in mm Hg.

In a state of rest, with each inspiration only 2/3 of the volume of the inspired air enters the alveoli and participates in gas exchange. The remaining portion stays in the respiratory tracts and does not participate in gas exchange. The space filled with air does not participate in gas exchange and is called *harmful (dead) space*. On the average, the volume of this space is 0.14 — 0.15 liters. As a result, in a state of rest only 0.36 liters reach the alveoli out of the total inspired air (0.5 liters).

TABLE 2.2

OXYGEN PARTIAL PRESSURE IN ATMOSPHERIC AND ALVEOLAR AIR AT DIFFERENT ALTITUDES (ξ_{O_2} = 21%) /29

Altitude, m	Atmospheric pressure, mm Hg	Partial pressure p_{O_2} in mm Hg		Altitude, m	Atmospheric pressure, mm Hg	Partial pressure p_{O_2} in mm Hg	
		Inspired (atmospheric) air*	Alveolar air**			Inspired (atmospheric) air*	Alveolar air**
0	760	159	105—110	5000	405	85	43—49
1000	674	141	87—92	6000	354	74	35—41
2000	596	125	75—79	7000	308	64	32—35
3000	526	110	60—67	8000	267	56	23—28
4000	462	98	50—59				

*Calculated according to Formula (2.2).

**Determined experimentally with allowance for hyperventilation.

The composition of expired air also differs from the alveolar air. This may be explained by the fact that at first (in a state of rest) about 0.14 liters of air is expired from the harmful space, whose oxygen content does not differ from the atmospheric air, and then — 0.36 liters of the alveolar air. Therefore, there is more oxygen in expired air than there is in alveolar air.

The values of p_{O_2} in atmospheric and alveolar air at different altitudes are given in Table 2.2.

It follows from the data in this table that, with an increase in altitude, the oxygen partial pressure both in atmospheric and in alveolar air decreases in a different manner. With an increase in altitude, the decrease in oxygen partial pressure in the alveolar air does not follow Formula (2.2), but depends on its content of carbon dioxide and water vapor.

In particular, at a human body temperature of 37° C, the partial pressure of water vapor is 47 mm Hg in the alveolar air, and the partial pressure of carbon dioxide is assumed to equal 40 mm Hg on the average.

Taking these data into account, the formula used to determine the oxygen partial pressure in alveolar air has the following form:

$$p_{O_2\ alv} = (B-47)\frac{\xi_{O_2}}{100} - p_{CO_2}, \qquad (2.3)$$

where B is the barometric pressure.

The effect of a decrease in p_{O_2} in the inspired air upon a human being ascending in altitude is characterized by the following data. Up to an altitude of 2 km, (p_{O_2} = 125 mm Hg) there are no significant changes in the human state of health, although objectively certain disturbances occur (reduction in sharpness of vision). This zone is arbitrarily called the *indifferent or zone of total compensation* [1].

At altitudes up to 2 and 3 km, the blood saturation with oxygen decreases to the point that the heart and lungs must work harder. A healthy human body can readily endure this, and therefore the zone encompassing altitudes up to 3 km (p_{O_2} = 110 mm Hg) may be called the *zone of sufficient compensation*. However, it must be stressed that staying at these altitudes for a long period of time (more than 4 — 5 hours) is accompanied by a strong reduction in working ability. /30

At altitudes greater than 3 km, the saturation of the blood with oxygen continues to decrease, since the human body cannot independently compensate for the increasing reduction in the oxygen partial pressure. At an altitude of 4 km (p_{O_2} = 98 mm Hg), due to a decrease in the difference between the oxygen partial pressure in the alveolar air and in the blood, oxygen diffusion from the lungs into the blood is slowed down to such an extent that *oxygen deficiency — hypoxia —* occurs.

Oxygen insufficiency in human blood is compensated by an increased respiration rate and an increase in its depth. Along with this, the respiration becomes nonuniform and discontinuous, deep inspirations alternate with surface inspirations, and the human ability for mental and physical work is appreciably reduced, as well as the coordination of movements, etc.

It is believed that in an untrained healthy individual, having no special protective devices against oxygen deficiency, at altitudes of 6 — 7 km there is practically complete loss of working ability and frequently a loss of consciousness, and at an altitude of about 8 km dangerous phenomena arise which can lead to death.

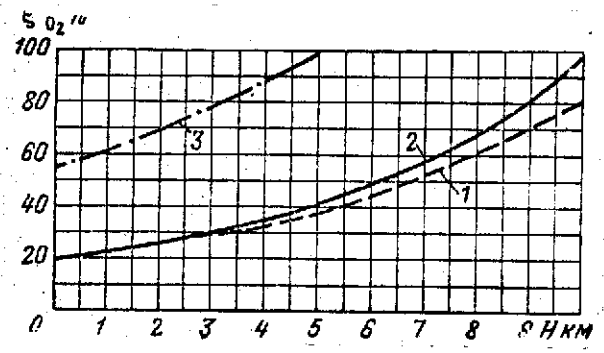

Figure 2.2. Dependence of percentile oxygen content in inspired air on flight altitude:

1 — no less than 160 mm Hg P_{O_2} in inspired air; 2 — no less than 110 mm Hg P_{O_2} in alveolar air; 3 — maximum oxygen content with no more than 420 mm Hg P_{O_2}.

As experience has shown, high human physical and volitional characteristics, long periods of high altitude training in barometric chambers or long periods of time in high mountains make it possible to increase these limiting altitudes.

Normal human activity with an increase in altitude may be secured by:

— Increase in the air pressure introduced into the cabin;

— Artificial increase in the percentile content of oxygen (ξ_{O_2}) in the inspired air with an increase in altitude (Figure 2.2);

— Increase in the oxygen pressure supplied for breathing.

The first method may be used in pressurized cabins of aircraft by supercharging them, i.e., by supplying to the cabins atmospheric air compressed from the engine compressors.

The second method may be used in ordinary oxygen devices by adding oxygen to the inspired air so that oxygen partial pressure in the alveolar air is no less than 110 mm Hg. In this case, conditions are produced which are similar to conditions at sea level, i.e., the blood is almost completely saturated with oxygen. /31

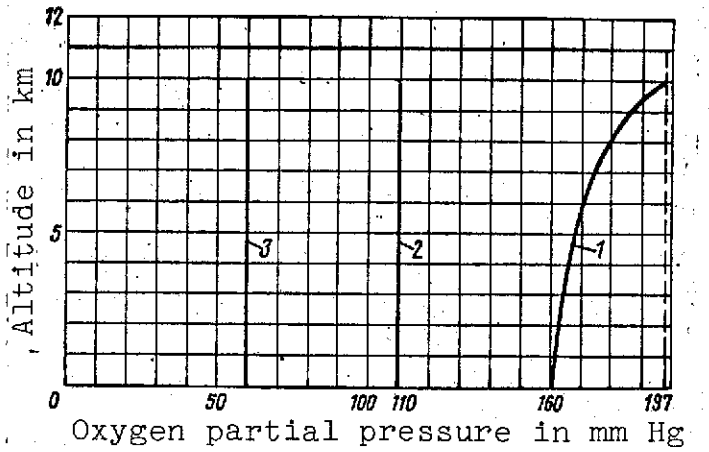

Figure 2.3. Change in oxygen partial pressure in inspired air with altitude for maintaining $p_{O_2\ alv}$ = 110 mm Hg.

1 — oxygen partial pressure in inspired air; 2 — oxygen partial pressure in alveolar air; 3 — oxygen partial pressure in alveolar air corresponding to the pressure at an altitude of 3 km.

Figure 2.2 shows the dependence of a change in the oxygen volumetric content in inspired air on flight altitude. The calculation was made according to the formula obtained from Equation (2.2). To maintain the oxygen partial pressure constant in the alveolar air at 110 mm Hg, the change in the oxygen volumetric content in the inspired air with altitude may be calculated according to Formula (2.3).

At an altitude of 10 km, pure oxygen is necessary for respiration. At an altitude of 11 km, the oxygen partial pressure in the alveolar air will be 82 mm Hg, and correspondingly 58 mm Hg at an altitude of 12 km. This altitude is the boundary above which breathing pure oxygen cannot protect the human body from oxygen deficiency.

The third method is used in oxygen devices with an excess pressure of the inspired air. However, the increase in oxygen pressure must be kept within certain limits for the following reasons:

— An increase over a long period of time in the oxygen partial pressure in the inspired air above 420 mm Hg may produce a toxic action, for example, pneumonia and edema of the lungs;

— With a pressure increase, human mobility in a space suit decreases and the weight increases.

It is apparent from the above statements that an oxygen partial pressure in the inspired air of about 160 mm Hg is necessary for the normal human activity. However, with a decrease in the barometric pressure, due to the fact that the partial pressure of water vapor and carbon dioxide in the alveolar air remains unchanged and is approximately 87 mm Hg combined, it is advantageous to increase the oxygen partial pressure in the inspired air at an altitude of 10 km up to 197 mm Hg (Figure 2.3).

If the cabin (space suit) becomes depressurized at altitudes /32
above 12 km or if the oxygen supply from the oxygen devices is stopped at altitudes greater than 7 km, the oxygen partial pressure in the inspired air sharply decreases and during the so-called reserve time sickness rapidly develops, which is caused by a sharp oxygen deficiency. *The reserve time* is that time which passes from the beginning of a sudden cabin (space suit) depressurization or from a cessation of the oxygen supply from the oxygen device up until the time that a limiting sick state develops, which usually is close to loss of consciousness as the

TABLE 2.3

CHANGE IN HUMAN RESERVE TIME WITH ALTITUDE

Cessation of oxygen supply from oxygen device and subsequent respiration of atmospheric air		Cabin (space suit) depressurization and subsequent respiration of pure oxygen	
Flight altitude km	Reserve time	Flight altitude km	Reserve time
7	4 — 9 min	13.5	18 min
8	2 — 4 min	14	2 min 45 sec
9	1 — 2 min	15	34 sec
10	40 sec	16	15 sec
11	35 sec		
12	25 sec		

result of a rapid oxygen deficiency. Experimental data on the reserve time are given in Table 2.3.

As has already been indicated, only a small part of the total oxygen inhaled by human beings (approximately 4%) is used by the body, i.e., this is the actual amount of oxygen required by the body ($q_{a.act}$). The remaining amount is expired from the lungs together with the expired air. Therefore, a great deal more oxygen may be supplied to the lungs than is used by the body [21].

The amount of oxygen required, and the amount of carbon dioxide expired, are usually measured in so-called normal liters $l(N)$, reduced to normal atmospheric conditions and (760 mm Hg and 15° C). /33

Data on the amount of actual oxygen required by man as a function of the work performed are given in Table 2.4.

TABLE 2.4

AVERAGE EXPERIMENTAL DATA ON PULMONARY VENTILATION, ACTUAL AMOUNT OF OXYGEN REQUIRED AND HEAT LIBERATION (HEAT PRODUCTION) OF AN ADULT (WEIGHT 60 — 70 kG, HEIGHT 170 — 180 cm) [2]

State of rest and type of work performed	Rate of external work, kG/m/min	Pulmonary ventilation, l/min	Actual oxygen required l(N)/min	Heat Production kcal/min
Rest	—	5 — 6	0.25—0.3	1.25—1.5
Very light work	—	6 — 10	0.3—0.5	1.5—2.5
Light work	—	10 — 16	0.5—0.8	2.5—4.0
Average work	250 — 450	16 — 25	0.8—1.2	4.0—6.0
Heavy work	450 — 800	25 — 40	1.2—2.0	6.0—10.0
Very heavy work	800 — 900	40 — 50	2.0—2.5	10.0—12.5
Extremely heavy work	900 — 1250	50 — 60	2.5—3.0	12.5—15.0
Exhausting work	More than 1250	More than 60	More than 3.0	More than 15.0

In manned spacecraft, the takeoff, landing, and other actions frequently impose great physical and emotional demands upon the pilot.

The amount of work performed by the pilot in carrying out these tasks may be qualitatively estimated based on a generally used gradation (light, average, and heavy work) and may be quantitatively estimated from the amount of heat liberated as follows:

Complexity of task	Average heat production in kcal/hour
Easy (simple) flight	150 (2.5 kcal/min)
Average flight	240 (4.0 kcal/min)
Difficult (complex) flight	350 (6.0 kcal/min)

In the human body, the liberation of carbon dioxide also depends on the composition of the food which is used. To oxidize 100 g of carbohydrates, 75 liters of oxygen are necessary, and 75 liters of carbon dioxide are liberated, i.e., the respiratory coefficient equals 1 ($CO_2/O_2 = 1$). In the oxidation of fats, the respiratory coefficient equals 0.71, and in the oxidation of proteins — 0.8. It may be assumed with a sufficient degree of accuracy in technical calculations that the respiratory coefficient changes from 0.8 to 0.9.

It has been established experimentally that when the carbon dioxide in the inspired air (pressure 760 mm Hg) reaches 3%, a feeling of inadequate air occurs. When its content is more than 3%, objective changes in breathing and circulation occur, and when its content is more than 5% — toxic effects and loss of consciousness occur [3]. It must be noted that when the inspired air pressure differs from normal (760 mm Hg), only the value of its partial pressure, and not the volumetric content, may be used to establish the danger of a certain concentration for human beings.

Figure 2.4 presents data on the human permissible concentrations of carbon dioxide in inspired air as a function of time. An increase in the carbon dioxide content in inspired air may be avoided by using circulatory ventilation of the space /34 suit or absorption of carbon dioxide in special devices.

In addition to carbon dioxide, expired air contains carbon monoxide (CO), ammonia (NH_3), acetone, and other gases. The content of carbon monoxide in expired air of healthy individuals is 0.0028 — 0.016 mG/l, ammonia — 0.000011 mG/l.

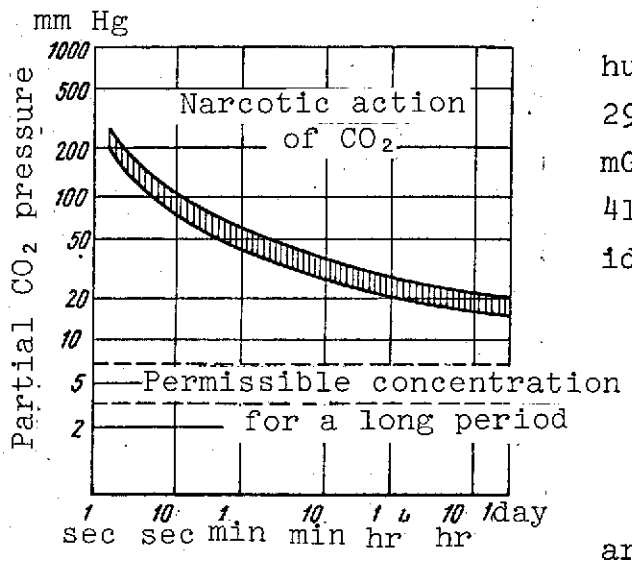

Figure 2.4. Change in permissible and dangerous concentration (partial pressure) of carbon dioxide in inspired air as a function of time.

It has been established that human respiration liberates 24 297 ± 156 mG ammonia, 278 ± 160 mG nonfuming carbon monoxide and 417 ± 211 mG fuming carbon monoxide, and 504 ± 333 mG hydrocarbons.*

2. Decompression Disturbances in the Human Body

Decompression disturbances arise in man at altitudes greater than 7 km due to the expansion of free gases existing in the semi-closed cavities of the body (in the middle ear, the gastroenteritic tract, lungs, and other locations) and their change from a dissolved state to a gaseous state when there is a great pressure drop in the external medium. These disturbances usually appear in the form of *high altitude pains* in the joints, *high altitude meteorism*, and *high altitude emphysema*.

High altitude pains arise 15 — 20 minutes (frequently in a few minutes) after reaching altitudes greater than 7 km, and are felt primarily in the large joints of the extremities, and frequently in the knee and arm joints. The painful sensations differ: from barely perceptible pains to very strong (intolerable) pains, which may even force the pilot to stop the flight. However, these pains do not always occur, and are not felt by everyone. Even in one and the same persons, they may not arise

*Problemy kosmicheskoy biologii (Problems of Space Biology), Vol. XI, Moscow, "Nauka" Press, Noscow, 1969.

in every flight [4].

These pains may be explained by the change of nitrogen and frequently carbon dioxide in the tissues of the body from the dissolved to the gaseous state when there is a great drop in pressure in the external medium. The gas bubbles thus produced may press on the nerve endings or clog up the small blood vessels.

To prevent the occurrence of high altitude pains, it is necessary to desaturate the body from nitrogen, i.e., to remove nitrogen by inhaling pure oxygen before the flight. The desaturation time depends on the future physical load. When pure oxygen is inspired, the nitrogen partial pressure in the alveolar air rapidly decreases, and the nitrogen in the lungs as well as the nitrogen passing into the lungs from the body tissues is given off with the expired air. Thus, in the case of desaturation due to blood circulation (tissue-lungs-tissue) the human body is gradually freed from the nitrogen dissolved in the blood and in the tissues, and the danger of high altitude pains is reduced [5].

The occurrence of high altitude meteorism may be explained by the fact that the gases, located in the human stomach and intestines, expand and increase in volume when the altitude increases (by approximately a factor of 5 at an altitude of 12 km). As a result, the intestines are extended and the abdominal diaphragm is compressed, the vital capacity of the lungs is decreased, and the position of the heart changes. During experimental human ascents to altitudes of 10 — 12 km in barometic chambers, individual cases of high altitude meteorism were observed which took the form both of pains in the lungs in the region of the stomach, and the form of a general heavy state of the body, ending in loss of consciousness.

High altitude emphysema takes the form of local subcutaneous swelling of the tissues, resulting from an increase in the gas volume in the tissues. It is known that any liquid boils when its vapor tension exceeds the external pressure. Therefore, it could be expected that a similar phenomenon would occur with the blood and the liquid in the tissues at a body temperature of 37° C, if atmospheric pressure is reduced to 47 mm Hg (which approximately corresponds to an altitude of 19 km). In actuality, the blood does not boil in the tissues due to the fact that the /35 necessary space for the production of the vapor is not present. Along with this, the volume of the gases and the tissues themselves increases. For example, at an altitude of 20 km, individual subcutaneous swelling occurs after 2 — 3 seconds. After 10 to 15 minutes, the fingers of the hands without gloves are increased in volume so much that the wrist of the hand cannot be used. After descending to an altitude below 17 km, the subcutaneous swellings disappear.

3. Pressure Drops During Cabin Depressurization (Explosive Decompression)

When the pressurization of a spacecraft cabin (or space suit) is disturbed, the cabin pressure decreases at a rate determined by the magnitude of the pressure drop, the cabin (space suit) volume, and the area of the opening through which the air (gas) passes, and equals the external pressure. Frequently this process takes place so rapidly (seconds or fractions of a second) that it appears to be an abrupt explosion; it is thus called *explosive decompression*. The effect of explosive decompression on human beings depends on the following:

— the initial pressure value and the rate at which it decreases in the cabin (space suit);

— the resistance of the human respiratory tracts and the devices in contact with them, for example, an oxygen mask;

— the general state of the human body.

In general, the slower is the rate at which the external pressure drops in the case of decompression, the less influence does it have.

A sudden and rapid pressure decrease in a cabin causes a sudden and rapid expansion and expiration of air from the lungs, just as with a strong cough. In the case of explosive decompression, high altitude pains may occur, as well as a sharp decrease in the blood pressure, a disturbance of the operation of the heart and local hemorrhages in the walls of the intestines, stomach, and lungs.

Based on the results of studies, a pressure decrease by 385 mm Hg in 0.4 seconds can be sustained by humans usually without any harmful influences. If a man uses an oxygen mask, which impedes the rapid expiration, then the unfavorable action of explosive decompression may be intensified [4].

4. Processes of Heat Liberation and Heat Emission in the Human Body

As a result of oxidation processes which are continuously taking place, the human body liberates heat, whose amount is determined by the actual oxygen requirement and basically depends on the physical work performed by man and factors in the surrounding medium (air temperature and humidity) (see Table 2.4). It has been established that a human being liberates about 5 kcal of heat with a consumption of 1 l(N) of oxygen. The

importance of heat liberation will become apparent from the following simplified calculation.

For a human weight of 70 kG and a body heat capacity equaling the heat capacity of water, the amount of heat liberated by a human in a state of rest (approximately 70 kcal per hour) increases the body temperature in two hours from 37 to 39° C when there is complete thermal insulation. For the majority of humans, such an increase in body temperature leads to a loss of operational efficiency. It is apparent that when performing physical work, the body temperature will increase even more rapidly.

It is apparent from this that the working capacity can be retained only if the heat liberated by man into the surroundings is artificially removed continuously, if the surrounding medium does not naturally cool the body to the normal temperature. In /36 this case, man will have to be cooled by the methods examined below.

A technical solution of the problem of human heat insulation must take the fact into account that for normal human functioning the temperature of the internal organs must be maintained with sufficient accuracy at a specific constant level (37° C). It is apparent that when a space suit is used for this purpose, a heat control system is required which interacts with the very complex natural system of automatic heat control of the human body itself.

Heat control processes in the human body

It has been shown experimentally that the limiting temperature of the human body, at which life may be maintained (but not the working capacity) must not be above 42 — 43 and not be below 27° C. Overall cooling of the body to a temperature of 22 — 24° C is possible under special conditions.

The temperature is maintained constant only in tissues which are located far under the surface of the human body. The temperature of the human body surface layer (which is up to 2.5 cm thick) changes greatly. Thus, under normal conditions, the average skin temperature under a jacket is 30 — 34° C. Under unfavorable meteorological conditions, at individual sections of the body, it may drop to 20° C, and sometimes lower.

A small part of the heat liberated by the human body is carried off into the surrounding medium through the body surface, and a small part — with the expired air.

On the average, the surface area of the skin, which depends on the height and weight, is 200 dm^2. The process of controlling the heat liberation in order to maintain a constant body temperature is performed by the human body by the three following methods: biochemical, change in circulation rate, and perspiration.

Biochemical heat control makes it possible to increase sharply the heat formation in the human body while maintaining the body temperature unchanged. This is done primarily by changing the rate of the oxidation processes occurring in the body. Thus, a muscle shiver, which occurs when the body is greatly cooled and which is accompanied by an increase in the

oxygen requirement, increases the heat liberation up to 110 to 170 kcal/hr [23].

When the human body is overheated, the blood vessels of the skin expand and a large amount of blood from the internal organs reaches it. Consequently, a large amount of heat is given off to the surrounding medium. The opposite phenomenon occurs when the body is overcooled: contraction of the blood vessels of the skin is accompanied by a decrease in the flow of blood to it and, consequently, less heat is given off to the external medium.

In the case of perspiration, the skin surface loses heat due to the evaporation of moisture. The movement of air contributes to more rapid evaporation of the perspiration from the skin surface, which explains the refreshing action of wind. In the case of a fever, when the temperature difference between the human body and the medium surrounding it decreases, the most effective method of removing heat from the human body is the liberation and evaporation of perspiration from the skin surface.

The zone in which the surrounding medium completely removes the heat liberated by the human body is called the *comfort zone*. This term characterizes a state of the medium under which it does not produce a feeling of cold or overheating.

With the normal composition and pressure of the atmospheric air (on the surface of the Earth), the comfort zone is characterized by definite relationships between the temperature, relative humidity, and air velocity. When there are significant deviations from these values, a feeling of discomfort arises, which is greater, the greater are these deviations. For aircraft cabins and space suits, the pressure and composition of /37

the atmosphere are also very important (for example, an oxygen-helium atmosphere, pure oxygen, etc.).

It is apparent that for contact or convection removal of the heat liberated by the human body, the temperature of the air adjacent to the human body must be somewhat lower than the temperature of the skin surface. The amount of heat thus removed is determined from the well-known heat transfer formulas. Existing types of equipment for removing heat will be examined in the corresponding chapters with respect to different types of space suits.

When the temperature of the cooling air increases to the temperature of the human body and above, the effectiveness of contact and convection heat removal is greatly reduced, and the removal of heat by evaporation of perspiration becomes of decisive importance.

Heat removed by the human body by means of perspiration evaporation

It has been established experimentally that the rate of perspiration excretion on the human body differs: in one person there is uniform perspiration excretion over the entire body surface, while on another person, there may be only slight perspiration excretion on the upper extremities and it may be more intense on other parts of the body surface. In the general case, zones with differing perspiration excretion may be used, as shown in Figure 2.5.

The amount of heat given off to the surrounding air from the body surface during the evaporation of perspiration primarily depends on the temperature, humidity, and velocity of the surrounding air, and on the vapor- and air-permeability of the

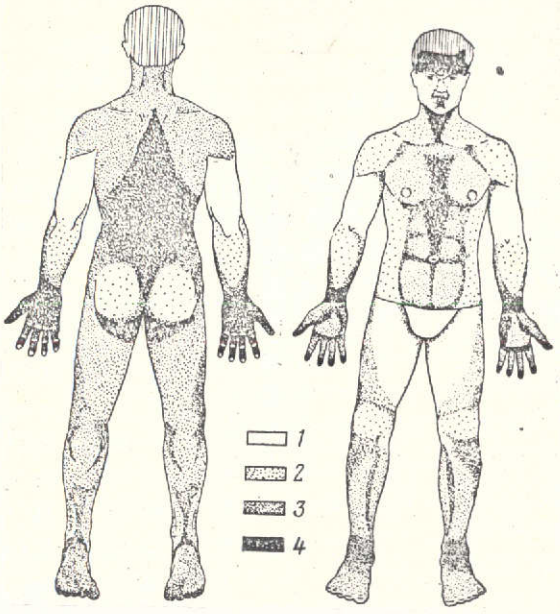

Figure 2.5. Zones of perspiration excretion intensity on the human body surface [23].

1 — minimal; 2 — slight; 3 — moderate; 4 — strong.

clothing. Table 2.5 gives data on the perspiration excretion as a function of air temperature and physical load.

Thus, for example, at an air temperature of 30° C for an individual who is not engaged in physical labor, the perspiration excretion through the skin is 120 G/hr, but when performing heavy labor, the perspiration excretion increases to 570 G/hr.

The relative air humidity has a great influence on the body heat output. Thus, with an increase in the air humidity, the rate of perspiration evaporation decreases, and the body heat output decreases. A high relative humidity at an air temperature above 30° C has a particularly unfavorable influence on man, since at this temperature almost all of the heat liberated by the body is given off to the surrounding medium in the evaporation of perspiration. At the same time, a relative air humidity which is /38 too low has an unfavorable influence on the mucus membrane of the eyes, the oral cavity, and the respiratory tracts. Therefore, for small periods of time (up to several hours) the relative permissible humidity is from 15 — 20 to 70 — 80%, and for long periods of time (days and more) it ranges from 40 to 60%.

TABLE 2.5

AMOUNT OF MOISTURE GIVEN OFF FROM THE SKIN SURFACE AND FROM THE HUMAN LUNGS IN G/min*(ACCORDING TO N. K. VITTE)

Characteristic of work performed	Air temperature in ° C				
	16	18	28	35	45
at rest (1.5 kcal/min)	0.6	0.74	1.69	3.25	6.2
light	1.8	2.4	3.0	5.2	8.8
average load (4.5 to 5.5 kcal/min)	2.6	3.0	5.0	7.0	11.3
heavy (6.5 — 7.5 kcal/min)	4.9	6.7	8.9	11.4	18.6
very heavy (10 kcal/min)	6.4	10.4	11.0	16.0	21.0

*Guminer P. I. Izicheniye termoregulyatsii v gigiyene i fiziologii truda (Study of Heat Regulation in Labor Hygiene and Physiology), Moscow, Mdegiz, 1962.

A human body weight loss of 2 — 3% by evaporation of perspiration is permissible (dehydration of the body). Dehydration by 6% disturbs the mental activity and lowers the vision, while dehydration by 15 — 20% leads to death.*

The amount of heat loss during the evaporation of perspiration is

$$Q_{e.p} = g_p r,$$

where g_p is the amount of perspiration excreted and evaporated in G/hr; r — latent heat of evaporation of water in kcal/kG.

The amount of moisture given off by man in the form of perspiration and with expired air is shown in Table 2.6.

*AIAA Paper No. 617, 1969.

TABLE 2.6*

AMOUNT OF MOISTURE GIVEN OFF FROM THE SKIN SURFACE AND WITH EXPIRED AIR IN A STATE OF REST (AVERAGE VALUES) AT DIFFERING AIR TEMPERATURES [19]

Air temperature in ° C	Relative air humidity in %	Total amount of vapors liberated in g/min	Amount of moisture given off in g/min	
			With expired air	With skin
10	75	0,60	0,18	0,42
18	70	0,74	0,17	0,57
28	55	1,69	0,13	1,56
35	50	3,25	0,11	3,11
45	35	6,2	0,09	6,11

*Commas in the numbers indicate decimal points.

The relative humidity of air supplied to hermetic cavities /39 of spacecraft and to space suits is frequently far below the optimum value at high flight altitudes for the following reasons.

The maximum moisture content of the air (kG/kG) depends only on its temperature, and decreases for atmospheric air with an increase in altitude (see Table A.2). When the atmospheric air in the engine compressor, which is supplied to the aircraft cabin, is compressed, the moisture content of this air does not change, but its pressure and temperature are increased.

Heat liberated by man with expired air

The amount of heat liberated by man with expired air depends on his physical load, humidity, and temperature of the surrounding (inspired) air. The greater the physical load and the lower the temperature of the surrounding medium, the more heat will be

removed with the expired air. The inspired air is heated in the lungs and is simultaneously saturated with water vapors.

In engineering calculations, we may assume (with a reserve) that the expired air has a temperature of 37° C and is completely saturated with moisture. Under these conditions, the amount of heat given off by the human body with the expired air is as follows due to its saturation in the lungs with water vapors

$$Q_{ex} = W\gamma_{in}(d_{37} - \varphi d_{in})r, \qquad (2.4)$$

where W is the pulmonary ventilation in m^3/hr; γ_{in} — specific weight of inspired moist air in kG/m^3; d_{37} — moisture content of air saturated with water vapors at a temperature of 37° C (d_{37} = 0.0392 kG/kG); φ — relative moisture of inspired air in %; D_{in} — moisture content of inspired air saturated with water vapor at a temperature of t_{in}; r — specific heat of vapor formation in kcal/kG.

The specific weight of moist air, which depends on its temperature, relative humidity, and pressure, may be found from the nomogram shown in Figure 2.6 [7].

The amount of heat consumed to heat the inspired air is

$$Q_{ex} = c_p W\gamma_{in}(t_{ex} - t_{in}), \qquad (2.5)$$

where c_p is the specific heat capacity of air; t_{in} — temperature of inspired air; t_{ex} — temperature of expired air.

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*Translator's Note: Expansion unknown.

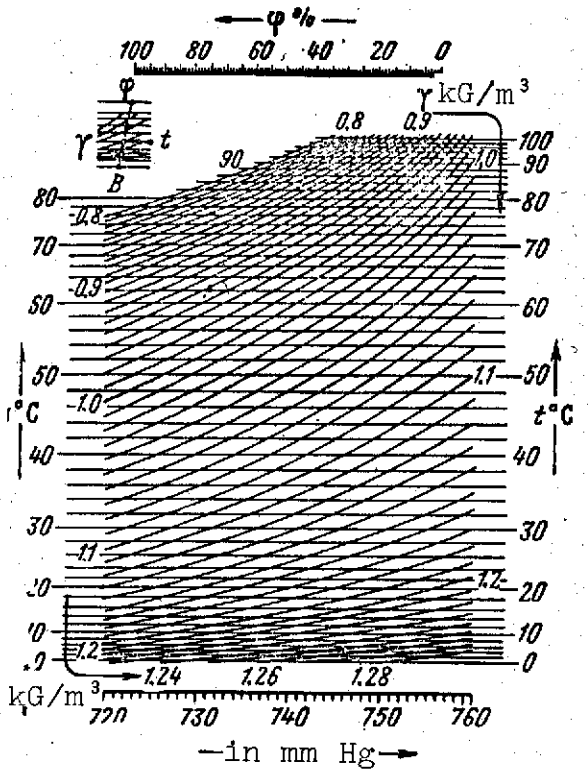

Figure 2.6. Nomogram for determining the specific weight of moist air at differing temperature, relative humidity, and barometric pressure [7].

γ — specific weight of air in kG/m³; t — air temperature in ° C; φ — relative air humidity in %; B — pressure in mm Hg.

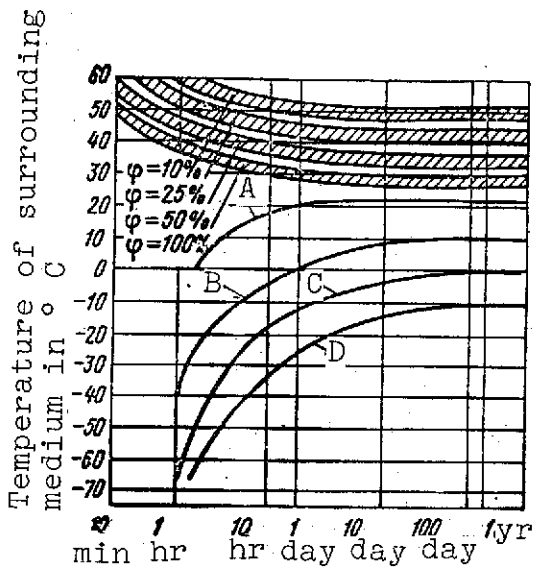

Figure 2.7. Tolerance limits to different temperatures of the surrounding medium.

A — light covering, 1 KLO;* B — special covering (jacket, wool underwear) — 2 KLO; C — regular flight jacket — 3 KLO; D — winter flight jacket — 4 KLO; φ — relative humidity in %.

With an increase in the temperature and humidity of the surrounding (inspired) air, the relative amount of heat given off through respiration decreases greatly.

Effect of high and low temperatures on man

Research has established that in air temperature of more than 30° C the working capacity of humans begins to decrease. Human heat tolerance, as well as sensations of heat, greatly depends on the moisture and velocity of the surrounding air.

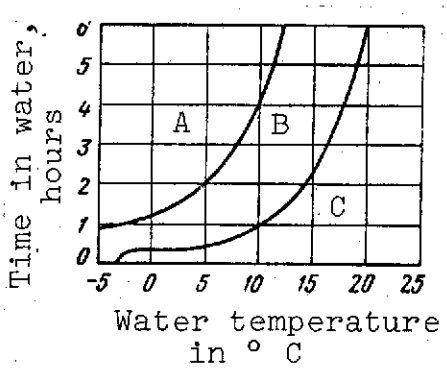

Figure 2.8. Influence of water temperature and duration of time in water on human condition.

A — dangerous for life; B — barely tolerable (50% mortality rate); C — tolerable.

Figure 2.7 gives approximate boundaries for human tolerance to low temperatures in differing clothing and to high temperatures for different values of the relative air humidity.

The greater the relative humidity, the less perspiration is evaporated per unit time and the more rapidly is the body overheated. The permissible amount of heat accumulated by the human body is usually determined by its amount per 1 m^2 of body surface. The critical limit for the accumulation of heat in the human body at rest is assumed to be 77 kcal/m^2, and 55 kcal/m^2 — in the case of light work. With these limitations, humans can tolerate /40 the following maximum high temperatures:

71° C for 60 minutes	93° C for 33 minutes
82° C for 49 minutes	104° C for 26 minutes

The maximum temperature of inspired air at which humans can breathe for several minutes is about 116° C.

The influence of water temperature on the human body is of great practical interest. Humans are rapidly cooled in the water due to its great heat capacity and thermal conductivity. Figure 2.8 shows experimental data on the influence of water temperature on a human submerged in water (without special clothing) [8].

5. Flight Overloads and Their Influence on the Human Body

At the present level of development of manned spacecraft, the human body in many cases cannot withstand the overloads arising during a flight without special protective devices. Therefore, the problem of increasing the resistance of the human body to the action of high overloads is of great practical importance, and a great deal of attention has been given to it.

An overload designates the ratio of the acting force to the force of gravity of the body.

We may use the following formula to determine the overload, taking into account the direction of the acting forces

$$\bar{n}=\frac{\overline{\Sigma F}}{|G|}, \tag{2.6}$$

where $\overline{\Sigma F}$ is the geometric sum or projection of the acting forces (excluding the force of gravity) in the direction in which the overload is established; G — force of gravity for the body.

Dividing the numerator and denominator of Equation (2.6) by the mass of the body, we obtain

$$\bar{n}=\frac{a}{g}, \tag{2.7}$$

where a is the acceleration of the body center of gravity which is transmitted to it by external forces; g — acceleration of the force of gravity.

As a dimensionless value, an overload is frequently measured in "units" (an overload of 3 units means that the acceleration from the acting forces is three times greater than the acceleration of the force of gravity).

An overload n = 1 means that only the acceleration of the force of gravity acts upon the body, and the overload is directed along the vertical to the center of the Earth. If the overload n = 0, then the body is in a state of weightlessness. This is possible if there is no acceleration, for example, during spacecraft flights with engines turned off outside of the fields of attraction (gravitation) of celestial bodies.

Overloads acting on a human in the "head-pelvis" or "pelvis-head" direction are called longitudinal. Overloads acting in the "chest-back" or "back-chest" direction are called transverse, and overloads acting from right to left or from left to right are called lateral.

Figure 2.9 shows overloads withstood by a human being in flight, as well as the signs characterizing their direction of action. Thus, the direction of the overloads is opposite to the /42 direction of the forces (acceleration) which cause these overloads.

The tolerance of the human body to overloads depends not only on its magnitude and direction with respect to the body, but also on the duration of action, the rate at which it changes in time, the physiological condition of the body, and other factors.

Overloads produce different deformations in the human organs and disturb their mutual location.

Examining the action of overloads on the human body, we must distinguish between the biological and physiological tolerance of the body to overloads. The biological tolerance is determined by the magnitude of the overload at which the vital activity is retained, but disturbances in the function

Figure 2.9. Name, direction, and signs of overloads acting on a human in flight. n_l — longitudinal overload; n_t — transverse overload; n_{la} — lateral overload.

of organs and systems of the human body are thus possible. The physiological tolerance is limited by overloads for which the human working capacity is retained and, as a rule, pathological disturbances of the entire body are absent [11].

The tolerance to overloads greatly depends on the direction of action with respect to the body. An overload which is the same in magnitude and duration in one direction may produce harmful results, while in another direction it may have no apparent influence.

When the force is applied very smoothly and is increased comparatively slowly, there is a smooth increase in the overload in time up to its final value. Therefore, in this case, the rate at which it changes in time (dn/dt) will be small, and the overload will not have any great influence. An impact overload increases at a very high rate and lasts for a very short period of time. The tolerance to an impact overload greatly depends not only on its magnitude, but also on the rate at which it increases. The greater the rate at which the overload increases, the greater the local stresses, deformation, and functional shifts in the human body.

Let us examine the effect of different overloads on a human being.

Longitudinal overloads (n_1). When overloads act for a comparatively long period of time in the "head-pelvis" direction, for example, when an airplane pulls out from a nosedive, the blood flows to the lower part of the trunk and the legs and its movement along the veins to the heart is slowed down. Thus, the blood pressure in the vessels of the head and the upper half of the body is reduced, and it is increased in the vessels of the lower extremities and the abdominal cavity. As a result, the blood supply to the heart, and particularly to the encephalon, is reduced, which has an extremely negative influence on the overall condition and working capacity of a human being. The organ of vision is particularly sensitive to an inadequate blood supply.

It is apparent that the longer is the action of these overloads, the more intensely will the negative phenomena caused by them develop and the lower will be the maximum permissible values of these overloads. For example, with longitudinal overloads ("head-pelvis") $n_1 = 2$, the efforts required to move the arms and legs become appreciable, and when $n_1 = 2.5$ it is almost impossible to rise from a seat. An overload of 3 — 4 units causes a feeling of general heaviness in the body (particularly arms and legs). In addition, the cheeks begin to sag, it becomes difficult to hold the head up, and it is difficult to breathe. If $n_1 = 3.5$, vision is reduced, and it seems as though there is a "grey veil" before the eyes. With a four-fold overload, there may be complete loss of vision, and with an overload of more than five units — if it continues more than 3 — 6 seconds — a sudden loss of consciousness occurs (fainting). When the overload is discontinued, vision is usually restored within 2 — 5 seconds, but consciousness is completely restored no sooner than several minutes. However, after consciousness is restored,

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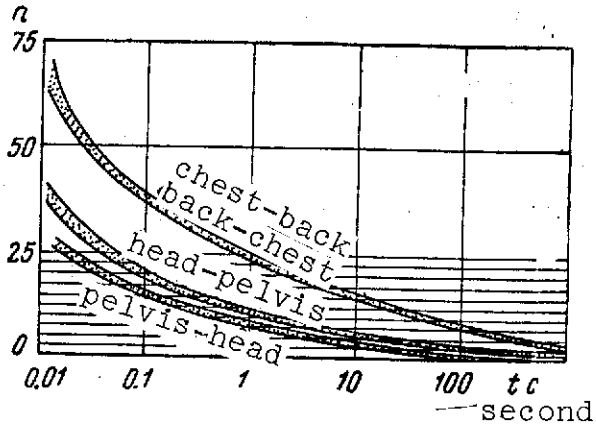


Figure 2.10. Human physiological tolerance to overloads in different directions (zones of individual differences are dashed) [10].

humans remain in a state of disorientation for 15 — 30 minutes, and sometimes more.

Data on the physiological tolerance to overloads in the "head-pelvis" direction are given in Figure 2.10.

With systematic training, some fliers can tolerate overloads of up to 6 — 8 units acting in the "head-pelvis" direction for several seconds, and an overload of 7 — 8 units — up to one second.

As has already been indicated, the physiological tolerance to an overload depends on the rate at which it increases. Thus, for example, for humans overloads of $n_1 = 4.5 — 5$ are permissible for humans when they increase at a rate of $dn_1/dt \approx 1$/sec, and at a rate of $dn/dt = 0.5$ 1/sec overloads of $n_1 = 5 — 6$ are permissible.

Overloads in the "head-pelvis" direction may be greatly attenuated by an anti-overload suit (AOS), whose protective action lies in the fact that the pressure exerted by it on the body decreases the amount of blood passing through the lower part of the body. The use of AOS increases the permissible overloads in the "head-pelvis" direction by approximately two units.

The ability of humans to endure considerable impact longitudinal overloads in the "head-pelvis" direction is of great importance. These overloads are produced when pilots are catapulted from aircraft in emergencies or when their parachute opens. Experiments have shown that 20-fold overloads in the "head-pelvis" direction for approximately 0.2 seconds are tolerated by humans without significant disturbances to vision or the nervous system. This may be explained by the fact that, due to the short duration of the overloads in these cases, the blood cannot move to the lower part of the body.

During flights, overloads in the opposite direction, "pelvis-head" are also possible, for example, during an abrupt nosedive or catapulting downward, etc.

During the prolonged action of overloads in the "pelvis-head" direction, the blood moves from the lower extremities and the abdominal cavity to the upper part of the body. As a result of this, the blood pressure in the vessels of the encephalon /44 sharply increases, and the greater the magnitude and duration of the overload, the more the blood pressure increases.

In a horizontal flight, the human body is affected by the Earth's attraction, and is subjected to a constantly acting, positive longitudinal overload ("head-pelvis") $n_1 = +1$, which is for him — just as on the surface of the Earth — a biological norm. When a negative overload occurs ("pelvis-head") $n_1 = -1$. In this case, humans experience the same feelings as when their head is upside down. When the overload acts for a comparatively long period of time $n_1 = -2$, there is a sharp pulsating pain in the head, and at $n_1 \approx -4$ humans lose consciousness.

With the brief action of a negative overload, its maximum permissible value increases. For example, an overload of n_1 = -8, -9 lasting for up to 1 second can be tolerated by man without any serious consequences.

Figure 2.10 gives approximate data on the permissible overloads in the "pelvis-head" direction.

Transverse overloads. Experiments on a centrifuge have shown that transverse overloads up to three units, acting for a long period of time (15 — 25 minutes) in the "chest-back" direction, can be tolerated by man in a seating position with no pain (see Figure 2.10). An overload n_t up to 4 — 5 for 7 — 10 minutes cannot only be readily tolerated by man, but does not hinder him from controlling an aircraft.

The great physiological human endurance in terms of transverse overloads, as compared with longitudinal overloads, may be explained by the fact that with transverse overloads, the blood pressure in the blood vessels of the human body increases much less than in the case of longitudinal overloads. Due to this fact, all of the disturbances to the circulatory system under the influence of overloads, which are caused by a change in the pressure and movement of the blood, are greatly reduced. A system of attached belts, which hold the trunk of a man firmly on a seat, are of great importance for protecting man in the seated position from the action of great transverse overloads in the "back-chest" direction. Experiments have shown that, if the trunk is held in a seat only by a belt around the waist, with an overload of n_t from -5 to -8 (abrupt slowdown of the aircraft), then a jerk of such force arises in the flight direction that damage may occur to the spine in the sacral-lumbar region, as

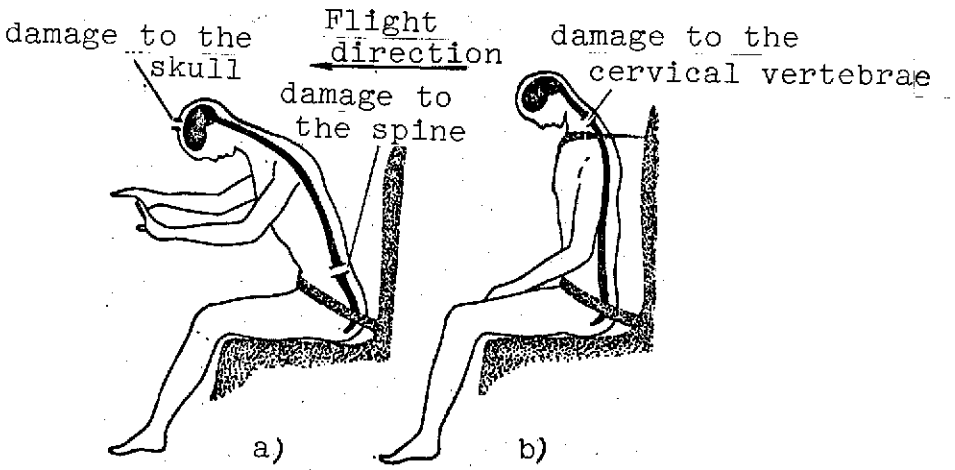


Figure 2.11. Possible damage to the human body when its trunk is attached to a seat by different methods.

a — only by belts around the waist; b — waist and shoulder belts.

well as damage to the skull should the head hit any object in the aircraft cabin (Figure 2.11).

If shoulder belts are used as well as belts around the waist, then if the aircraft stops suddenly and the head snaps forward from the back of the seat, damage to the cervical vertebrae are possible (see Figure 2.11).

As experiments have shown, in a reclined position on the back or the stomach, man can tolerate an overload of n_t = 10 to 12, acting for 150 — 180 seconds (Figure 2.12). When lying on the back, the overloads may be tolerated more easily if the human body is inclined at an angle of 10° — 15° to the ground in the direction of the acceleration, and the angle of inclination of the hip to the trunk is 80° — 120°. In this position, test subjects have tolerated overloads up to 16 units, lasting for 50 seconds. In this position of the trunk and the feet, with /45

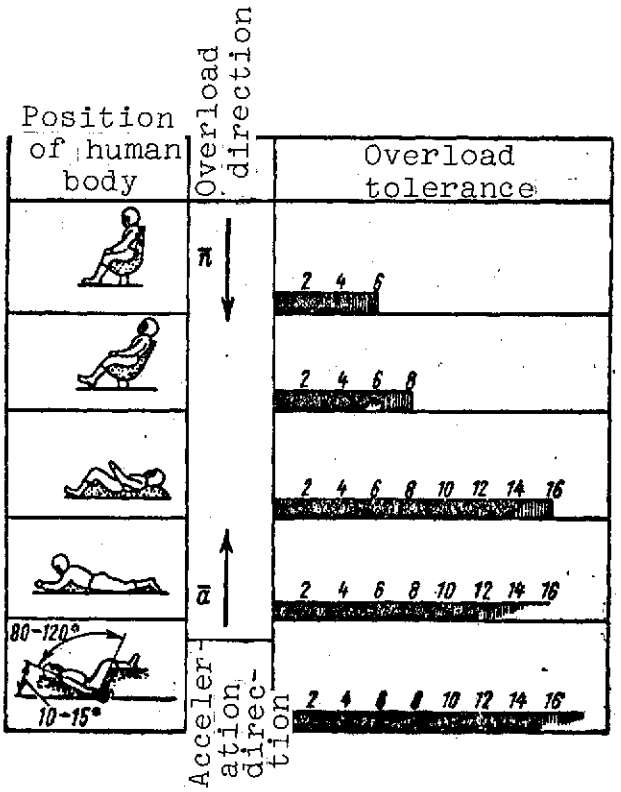


Figure 2.12. Influence of the body position upon tolerance to transverse overloads.

an overload direction of action which is opposite to that shown in Figure 2.12, the tolerance to transverse overloads greatly decreases and with an overload of $n_t = -8$ the test subject feels the blood rushing to his head, has shortness of breath and pains in the chest and the feet.

The problem of the physiological tolerance to transverse impact overloads is of great practical importance. It has been established by tests that impact overloads in the "chest-back" up to $n_t = 46$ and in the "back-chest" direction up to $n_1 = -35$ for 0.37 seconds are permissible for man.

Lateral overloads act upon man in the "side-side" direction from right to left or from left to right (Figure 2,9). It is usually assumed that the physiological tolerance to lateral overloads is approximately the same as to transverse overloads.

Overloads during rotation arise both during uniform rotation, or when it is accelerated or slowed down. In the first case, they arise from the action of constant centripetal acceleration, passing along the radius toward the center, and in the second case — from the concurrent action of centripetal and tangential acceleration. Since the latter is directed along the tangent to the circle of rotation (perpendicularly to its radius), the magnitude and direction of the resulting acceleration in this case may be determined by the geometric sum of both these accelerations, and in the general case the vector of this acceleration is not constant in terms of magnitude or direction. The overload thus produced is determined according to Formula (2.7) by replacing the acceleration a by the centripetal or resulting acceleration. The human vestibular apparatus is very sensitive to this type of overload. The data in the literature regarding the irritation threshold* /46 of the human vestibular apparatus during rotation are very contradictory. Many researchers indicate that rotation at an angular velocity of 1.5 rad/sec can be perceived by man. There is no doubt that acrobats perform a double somersault at an angular rate up to 30 rad/sec (1719 deg/sec), but the time of action of this overload is very small.

The action of overloads during repeated rotations has been studied on humans, within limits corresponding to the human physiological tolerance to overloads, and on animals until their death. The tests were carried out with the test subject lying on his side. If the axis of rotation passed through the heart, then after twelve seconds at a rotation rate of 2.6 rev/sec the test subjects lost consciousness [12]. Narcotisized animals died after two minutes at a rotation rate of 3.3 rev/sec. Humans can

*The threshold of irritation in physiology and psychology is called the smallest value for the force of the action causing a feeling of irritation in the corresponding nerve center.

endure rotation at an angular velocity of 1.5 rev/sec for one minute, and rotation at an angular velocity of 2 rev/sec for one-half minute.

Weightlessness. The customary feeling of the force of gravity disappears for humans in a state of weightlessness.

On 12 April 1961 the Soviet cosmonaut Yu. A. Gagarin was the first human in the world to fly on the spacecraft Vostok-1 in a state of weightlessness for about an hour, and had no particular difficulties in reading, writing, and performing the necessary observations under these conditions. This was very important for subsequent space flights.

The action of weightlessness on the human body is manifested in a reduction of the mechanical stresses (pressure) caused by the force of gravity. This lowers the working capacity of the cosmonauts and weakens the muscles in the legs and back.

When humans are in a state of weightlessness, the blood hydrostatic pressure disappears, and the cosmonauts experience a strong rushing of the blood to the head, and the heart gradually begins to function with a reduced load. During weightlessness the weight of the blood ceases to be the regular stimulant for the circulatory system, which in time reduces the efficiency of these mechanisms.

The American cosmonauts who flew to the Moon under the Apollo program were in a state of weightlessness for more than ten days.

Medico-biological studies performed on A. G. Nikolayev and V. I. Sevast'yanov during and after the flight, who were on the spacecraft Soyuz-9 for 18 days, showed that the state of weightlessness had no harmful influence on their bodies.

It is still impossible to answer the question of how a more prolonged state of weightlessness will affect the human body. Only experience founded on long space flights will make it possible to study this problem thoroughly.

The problem of man traveling through space in a state of weightlessness is of great practical importance. Many have assumed that animals and humans living on the Earth could not rotate their body around any axis in space.

The results of research performed in space flights have confirmed the fact that, after certain preparation, humans can rapidly and precisely turn in any direction in a state of weightlessness [16].

6. Influence of Vibration and Noise /47

Vibrations. The protection of humans from vibrations is a serious problem. This problem is very urgent, due to the fact that in the near future aircraft and spacecraft will have flight velocities and engine power which will constantly be increasing. Both during launching and in flight (in the powered portion), spacecraft undergo vibrational overloads, which may exceed the norms which are permissible for humans in terms of frequency and amplitude.

During vibrations, the oscillation rate continuously changes. Consequently, variable accelerations are produced all the time.

In oscillatory motion, the maximum acceleration is determined from the formula

$$a_m = 4\pi^2 J^2 b,$$

where J is the oscillation frequency in Hz; b — oscillation amplitude in mm or cm. The vibration intensity is characterized by the vibrational overload

$$n_v = \frac{a_m}{g} = \frac{4\pi^2 J^2 b}{9810} \approx \frac{J^2 b}{250}. \qquad (2.8)$$

Different disturbances arise in the human body under the influence of vibrations. These disturbances are caused not only by the local action of vibration on the organs and tissues, but also by their overall influence on the nervous system. For example, under the action of intense vibrations the pulse accelerates or slows down, and in the majority of cases the arterial blood pressure decreases.

Along with these objective results of vibration, many authors point to the possibility of the occurrence in man of general fatigue, irritation, pains in the head, noise in the head, etc [13, 14].

Under flight conditions, the noise from the engines and the air stream passing around the spacecraft to a significant degree intensifies the action of vibrations on man, and pilots frequently complain of the fatiguing action of the noise. In actuality, this fatigue arises due to the simultaneous action of noise and vibrations.

It has been established experimentally that the action of vibrations on the human body depends on their frequency, amplitude, and direction of action with respect to the human body. It must not be assumed that the higher the oscillation amplitude, the more dangerous are the effects caused by them. Experiments have shown that in many cases oscillations with large amplitudes but low frequency were much less harmful than oscillations with low amplitudes but a higher frequency.

A comparison of the frequency of oscillations of spacecraft and the eigenfrequency of the oscillations of the human body and its individual parts shows that the action of vibrations on the body is the strongest. Certain authors assume that the frequency of vibrations at which resonance phenomena arise in the human body equals 5 — 8 and 20 — 25 Hz [14].

The vibrations which are propagated along the body are not felt as strongly as their action is weaker when man is in a standing position, rather than in a sitting position. Horizontally, directional vibrations have approximately the same effect as vibrations along the body.

Figure 2.13 shows the results of vibrations with different frequencies and amplitudes upon a man fastened to a rigid seat with a belt for several days [8]. The action upon humans of shorter vibrations has not been studied sufficiently. However, the results of numerous experiments performed up to the present provide a basis for assuming that this action will be much less pronounced than in the case of long vibrations.

Certain authors [15] have estimated as follows the tolerance /48
to vibrations of a man seated in an aircraft seat for several hours.

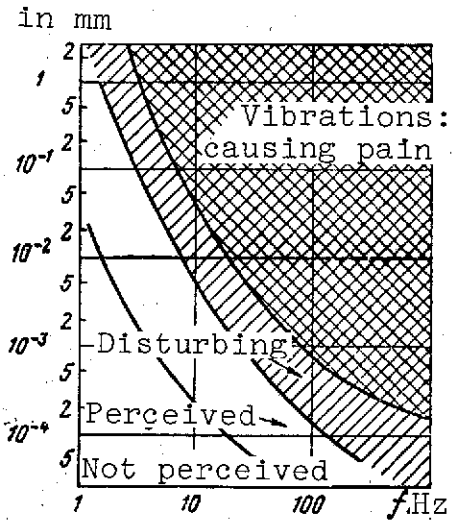


Figure 2.13. Human reaction to vibrations [8].

Region of readily tolerated vibrations. Vibrations in this region do not cause any significant changes in the body or unfavorable subjective feelings. These include vibrations with a frequency of 10 — 30 Hz and an amplitude up to 0.8 mm, and also with a frequency of 40 — 60 Hz and an amplitude up to 0.4 mm.

Region of tolerable vibrations. Under the action of these vibrations insignificant, readily reversible functional changes occur which are not accompanied by clearly expressed subjective feelings and which do not lead to a significant reduction in the human working capacity. They disappear after the vibrations have stopped. This region includes vibrations with a frequency of 10 Hz and an amplitude up to 1.6 mm, as well as with a frequency of 50 Hz and an amplitude up to 0.8 mm.

Noise. Noise occurring during aircraft flights frequently reaches very high intensities, and in this case has a harmful influence on the human body and lowers the working capacity. To a significant extent, humans are accustomed to noise, but its prolonged action may gradually lead to a reduction in hearing, and after several years under the influence of noise humans may completely lose their hearing. Under the influence of noise, vision is dulled.

Acting upon the encephalon, noise accelerates human fatigue, distracts attention from the surroundings, and slows down the psychic reactions.

The extent of the harmful influence of noise upon humans depends upon the intensity, duration of action, and frequency (spectrum) of noise. The higher the frequency of sound oscillations, the more harmful is its action upon humans.

Noise is characterized by a frequency composition and sound pressure (sound force level). Noise is called low frequency if its spectrum predominantly contains sounds with a frequency up to 300 Hz, average frequency — from 300 to 800 Hz, and high frequency — 800 Hz and higher.

A dyne per square centimeter (dyne/cm^2), which comprises 10 N/m^2 is used as a unit of sound pressure p.

To measure sound intensity, W/cm^2 erg/sec/cm^2 are used as a unit.

Sound intensity as a function of sonic pressure is determined from the formula

$$I = \frac{p^2}{\gamma c}, \qquad (2.9)$$

where p is the sound pressure in dyne/cm^2; γ — specific weight of the medium in G/cm^3; c — speed of sound in cm/sec.

The human ear can perceive only a certain range of sound frequencies — from 16 to 20,000 Hz, and also a certain range of sound pressures (dynamic range).

The dynamic perception range has a lower limit which is the *threshold of hearing sensitivity* and an upper limit which is *the threshold of pain sensation.*

Barely perceptible sounds, which produce a sound pressure of $p_0 = 2 \cdot 10^{-4}$ dyne/cm^2 at a frequency of 1000 Hz, correspond to the threshold of hearing sensitivity, which is used as a unit of comparison. /49

Sounds which are not perceived as sound, but cause painful sensations in the hearing organs, and produce a pressure of $p = 2 \cdot 10^2$ dyne/cm^2 at a frequency of 1000 Hz, correspond to the threshold of pain sensation.

Thus, the energy of sound on the boundary of a pain sensation exceeds by 10^6 the audibility threshold energy.

This enormous range of values in sound pressure and intensity is not expressed by multiple digit numbers, but by the logarithms of the ratios of these values to the values corresponding to the audibility threshold with a standard frequency equal to 1000 Hz. These ratios are usually called the *intensity levels* (force) of sound.

The bel (B) is used as the unit to measure the force of sound. An increase in the force of sound by a factor of ten corresponds to 1 B, and by a factor of 100 — to 2 B, etc.

The human hearing organ can distinguish an increase in the force of sound by 0.1 B. Therefore, a decibel (dB) is used in practice to measure sound.

The level of the force of sound is determined according to the formula

$$L = 10 \lg \frac{I}{I_0}. \qquad (2.10)$$

The intensity (force) level of sound may be determined from the sound pressure, since the sound intensity is proportional to the square of the sound pressure

$$L = 10 \lg \frac{I}{I_0} = 10 \lg \frac{p^2}{p_0^2} = 20 \lg \frac{p}{p_0} \text{ dB}$$

It is very advantageous to use a scale of decibels. The enormous range of sound intensity, from barely perceptible to deafening loudness, may be established between 140 — 150 dB. When determining the different levels of sound, this makes it possible to use small whole numbers (from 8 to 150), since changes in the sound force level less than 1 dB can usually not be perceived.

Human hearing is most sensitive to frequencies from 500 to 4000 Hz. This region is characteristic for sounds of human speech. It has been established by experiments that sounds which have one and the same force level, but different frequencies, produce a sensation of differing loudness in humans. This makes it necessary to introduce a new acoustical value — *the sound loudness level* with a unit of measurement — the phon (quantitative phons are also measured in decibels).

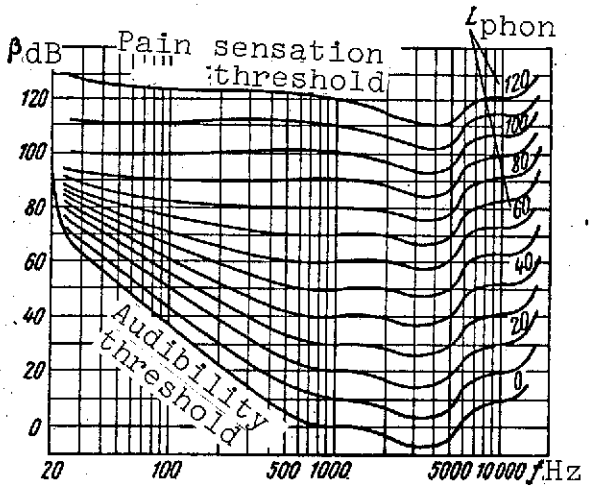


Figure 2.14. Curves showing differing sound loudness in phons at different frequencies in Hz and sound force levels in dB [8].

Figure 2.14 shows the dependence of the physiological perception of sound loudness (in phons) on its frequency and force level of the standard sound, obtained from data in mass experiments.

The minimum level of noise force, at which the fatiguing action of noise on the hearing organ appears, differs and depends on the frequency-components of the sound.

According to Soviet official norms (SN-245 — 71), the total noise level in dB as a function of the frequency range does not exceed:

At a frequency of Hz

	63	125	250	1000
In design offices	71	61	54	45
In laboratories	94	87	82	75
In industrial plants	103	96	91	85

The total noise level in the cabins of passenger planes is limited by the following values in dB (standard 503AT 30.VI.62):

Frequency in Hz

/50

	106	425	850	1700	3400	6800
Flights up to 2 hours	99	89	79	63	58	49
Flights more than 2 hours	94	84	74	63	53	44

Significant disturbances in hearing and in the central nervous system occur as a result of noise with a force level up to 110 dB for several hours. The repeated action of noise with a force level of 120 dB for three hours leads to clearly expressed changes in the body [3]. Noise above 140 dB for several hours causes nausea, impairs the vision, and increases the skin temperature.

Table 2.7 gives the loudness levels for certain noise.

In the cabins of aircraft, noise may be reduced by reducing the noise in the source itself, by using sound insulation and also by using headphones with sound insulation.

The sound-insulating properties of materials may be characterized by their sound conductivity coefficient

$$\tau = \frac{\text{sound energy passing through material}}{\text{sound energy falling on material surface}}$$

The degree of sound insulation of a given object (in dB) is determined from the formula

$$SI = 10 \lg \frac{1}{\tau}. \qquad (2.11)$$

It follows from Formula (2.11) that to decrease the sound level of external noise of 110 dB by 30 dB it is necessary to use sound insulating material whose coefficient τ equals 0.001, i.e., the material must be able to reduce noise passing through it by a thousand times.

TABLE 2.7

LOUDNESS LEVELS OF DIFFERENT NOISES [14]

Source or location of noise	Noise frequency characteristic	Loudness level
Whisper (soft)	—	10 phons
Radio (quiet transmission)	—	40 phons
Loud conversation	—	70 — 75 phons
Electric engine	Low frequency	40 — 60 phons
In passenger cabin of aircraft IL-18	Low frequency	97 — 100 phons
In pilot cabin of aircraft IL-18	Low frequency	105 — 106 phons
Automobile signal	Low frequency	85 — 95 phons
Telephone bell	Low frequency	60 phons
Aircraft jet engines	Average frequency	110 — 140 dB and more
Aerodynamic (vortex) noise	High frequency	up to 175 — 180 dB

Objects with layers (with air gaps) have a higher sound insulating coefficient than do solid objects. This may be explained by the fact that the surface of the first layer begins to oscillate, like a diaphragm, under the action of a sound wave. These oscillations are transmitted to the following /51 dense layer to a reduced degree, since the transmission does not take place directly, but through an intermediate air layer.

The average values of τ and D for certain materials are given in Table 2.8.

TABLE 2.8

AVERAGE VALUES OF DEGREE OF SOUND INSULATION D AND SOUND CONDUCTIVITY COEFFICIENT τ FOR CERTAIN MATERIALS [14]

Name of material, its thickness	Weight 1 m^2/G	Degree of sound insulation D, dB	Sound conductivity coefficient
Wool fabric, 2 mm	—	5 — 6	0.25
Solid container, 5 mm	3,000	16	0.025
Cork slab, 50 mm	30,000	20	0.01
Aluminum alloy D16, 0.5 mm	1,400	15	0.03
Silicate glass, 3 — 4 mm	12,000	28	0.0016

7. Biological Influence of Ionizing Radiation

A general characteristic feature of all ionizing radiation is the ability to produce in the human tissues, through which they pass, electrically charged particles — ions.

Ionization of the tissues arises not only due to the direct action on humans of different forms of external ionizing radiation, but also due to the continuous radiation of radioactive isotopes, which are formed in the body under the action of this radiation, and which enter the body with water, food, and possibly the air.

With comparatively long periods of half-life (decomposition /52
duration of half of the initial amount of a given radioactive substance), these isotopes may accumulate in the body and produce prolonged internal radiation and ionization within it.

There are three groups of radioactive isotopes which can accumulate in the human body:

(a) Isotopes which are primarily located in the bones and disturb the blood-producing capacity of the body;

(b) Isotopes which are uniformly distributed throughout the entire body and produce general ionization of the body.

Recently, a great amount of attention has been devoted to studying the action of the nuclei of light elements comprising both primary space radiation and radiation during solar flares.

Although the total relative amount of such nuclei is very small, based on calculations for primary space radiation their contribution to the total biological dose may exceed 70%. This may also be the case for radiation in the case of solar flares, during which the amount of nuclei of light elements may be very great when the flares are of high intensity.

Proton emission, which is practically absent under terrestrial conditions but which is of decisive importance for orbital and interplanetary flights, as compared with X-ray, has a much greater influence on the blood-producing process, which is more unfavorable in the oncological and genetic respects, but has less of an influence on the overall course of radiation sickness.

Maximum permissible doses. In a large amount of experimental material with animals, as well as studies on experiments with humans with X-rays and γ-rays, doses of radiation have been established for which there are no irreversible changes in the human body. These doses are called the *maximum permissible doses*.

For humans whose work subjects them to the action of ionizing radiation, the total dose of all types of radiation must not exceed 0.1 Rem/week* [17].

*The total dose of all natural radiation sources on the surface of the Earth acting upon humans is approximately 0.4 — 2 mRem/day.

It is assumed that a lethal dose of radiation is 400 to 600 rads for humans. Rabbits die at 800 to 1000 rads, and the simplest unicellular organism — infusoria — dies at 350,000 to 600,000 rads.

It is well known that short orbital flights passing below the radiation belts of the Earth and during the period of a "quiet" Sun, do not represent great danger for cosmonauts.

Dosimetry devices on board the Soviet spacecraft Vostok and Voskhod showed that the total doses of ionizing radiation received by the cosmonauts were on the order of 10 — 80 mRem/day.* This is much less than the dose which humans receive during X-ray radiation of the lungs or the stomach.

However, during flights along the Earth-Moon-Earth trajectory or above the radiation belts of the Earth, spacecraft crews may receive a radiation dose which greatly exceeds the norms of professional radiation on the Earth given above. For technical reasons, it is very difficult to place on spacecraft overall protection from penetrating radiation, which could reduce the radiation dose to a controlled level.

In this connection, certain researchers have proposed introducing a special classification of radiation levels, which may be used when evaluating the radiation danger during space flights [18]:

— permissible dose (PD);
— dose of calculated risk (CRD);
— critical dose (CD).

*1 mRem = $1 \cdot 10^{-3}$ Rem.

PD is the dose of ionizing radiation which does not have /53
any great influence upon humans throughout their lifetime.

CRD is the dose of ionizing radiation which can cause slight clinical symptoms of radiation damage.

CD is the dose of ionizing radiation which leads to great clinical symptoms of radiation damage, but without causing death.

At the present time, it is possible that the cosmonauts during their flights may receive a total dose of radiation of about 25 Rem, whereas the CRD is approximately 50 Rem, and the CD does not exceed 125 Rem during brief flights [19].

Radiant energy

The world of radiant energy, in which mankind exists, includes rays of different physical characteristics and differing physiological action upon humans: infrared (740 — 0.76 μ), visible (760 — 400 Nm), and ultraviolet (400 — 5 Nm).

Infrared rays basically have a thermal influence upon the human body. The absorption of the energy of these rays occurs in the epidermis. Part of the rays penetrate through the skin and the bones of the skull (1%).

In the long wave region from 0.8 to 1 micron, the human skin reflects about 30% of the incident radiation and about 4% in the wavelength range from 4 to 50 microns. Humans themselves radiate infrared rays from 5 to 25 microns.

Cataracts are the most frequent and serious damage to the eyes from the action of infrared rays.

The visible portion of the solar spectrum, which occupies an intermediate position between ultraviolet and infrared rays, has a specific action upon the skin and the organs of sight. Almost all of the violet portion of the visible spectrum has a burning action, and its red portion approximates the action of infrared rays.

The Sun produces the greatest illumination values — up to 100,000 lux on a surface perpendicular to the rays. On a horizontal surface (at a latitude of 60°), the illumination amounts to 72.4 klux.

A surface is illuminated by the direct light of the Sun or by scattered light — particles of air, so-called diffused light of the atmosphere. Horizontal diffuse radiation when the Sun rises and sets is on the average about 1,000 lux.

Ultraviolet rays (UVR) are electromagnetic oscillations with a wavelength from 400 to 5 Nm, which may be subdivided into the near waves — from 400 to 10 Nm, and the far waves — from 10 to 5 Nm.

The skin and the eyes of the human body are directly influenced by ultraviolet rays.

UVR with a wavelength of about 290 Nm has the greatest erythematous influence (coloring of the skin). UVR damages the cornea and conjunctiva of the eyes (λ = 250 Nm), causing a disturbance of the vision at 4 mW/sec/cm^2 (1/8 of the erythematous dose [22]).

REFERENCES

1. Lavnikov, A. A. Aviatsionnaya meditsina (Aviation Medicine), Moscow, Voyenizdat, 1963.

2. Kratkiy spravochnik po kosmicheskoy biologii i meditsine (Short Handbook on Space Biology and Medicine). Edited by A. I. Burnazyan, et al. Moscow, Meditsina, 1967.

3. Chelovek pod vodoy i v kosmose (Man Under Water and In Space), Collection of articles edited by O. G. Gazenko and A. M. Genin, Moscow, Voyenizdat, 1967.

4. Tsivilashvili, A. S. and I. N. Chernyakov. Influence of Explosive Decompression on the Organism of Animals and Man. Voyenno-meditsinskiy zhurnal, No. 9, 1961.

5. Viollett, F. Vzryvnaya dekompressiya i yeye deystviye na organizm cheloveka (Explosive Decompression and Its Action on the Human Body), Moscow, Voyenizdat, 1961.

6. Kuno, Ya. Human Perspiration. Moscow, Foreign Literature Press (IL), 1961.

7. Oppl, D., Iokl, M. Metodika izmereniya mikroklimaticheskikh /54
usloviy v gigiyenicheskoy praktike (Methods of Measuring Microclimatic Conditions in Hygienic Practice), Moscow, Medgiz, 1962.

8. Vudson, U. and D. Konover. Spravochnik po inzhenernoy psikhologii dlya inzhenerov i khudozhnikov-knostruktorov (Handbook on Engineering Psychology for Engineers and Designers), Moscow, Mir Press, 1968.

9. Gavrilov, V. A. Prozrachnost' atmosfery i vidimost' (Atmospheric Transparency and Visibility), Moscow, Gidrometeoizdat, 1958.

10. Umanskiy, S. P. Bar'yer vynoslivosti letchika (Fatigue Barriers for Pilots), Moscow, Mashinostroyeniye, 1964.

11. Kosmicheskiaya biologiya i meditsina (Space Biology and Medicine), collection of articles edited by V. I. Yazdovskiy, Moscow, Nauka Press, 1966.

12. Meditsinskiye problemy bezopasnosti poleta (Medical Problems of Flight Safety), Moscow, Voyenizdat, 1962.

13. Borshchevskiy, I. Ya. and E. V. Lapayev. Influence of Aviation Noise of Differing Intensity and Duration. Voyenno-meditsinskiy zhurnal, No. 2, 1965.

14. Slavin, I. I. Proizvodstvennyy shum i bor'ba s nim (Industrial Noise and the Fight Against It), Moscow, Profizdat, 1955.

15. Borshchevskiy, I. Ya, et al. Influence Upon the Human Body of Vibrations from Certain Types of Aircraft and Helicopters. Voyenno-meditsinskiy zhurnal, No. 1, 1958.

16. Stepantsov, V., et al. In Open Space. Aviatsiya i kosmonavtika, No. 7, 1965.

17. Moyseyev, A. A. and V. I. Ivanov. Kratkiy spravochnik po radiatsionnoy zashchite i dozimetrii (Brief Handbook on Radiation Shielding and Dosimetry), Moscow, Atomizdat, 1964.

18. Grigor'yev, Yu. G., et al. Problem of Establishing Permissible Doses for Spacecraft Crews. Problemy kosmicheskoy biologii (Problems of Space Biology), Moscow, Nauka Press, Vol. VI, 1967.

19. Barton, A. and O. Edkholm. Man Under Cold Conditions. Moscow, IL, 1957.

20. Vitte, N. K. Teplovoy obmen cheloveka i yego gigiyenicheskoye znacheniye (Human Heat Exchange and Its Hygienic Importance), Kiev, Medgiz, USSR, 1955.

21. Berkovich, Ye. M. Energeticheskiy obmen v norme i patologii (Energy Exchange in Standards and Pathology), Moscow, Meditsina, 1964.

22. Galanina, N. V. Luchistaya energiya i yeye gigiyenicheskoye znacheniye (Radiant Energy and Its Hygienic Importance), Moscow, Meditsina, 1969.

23. Sheykin, A. A. Trudy III Vsesoyuznoy konferentsii po aviatsionnoy i kosmicheskoy meditsine (Transactions of the Third All-Union Conference on Aviation and Space Medicine), Moscow, 1969, Vol. II.

CHAPTER 3

LIFE SUPPORT SYSTEMS FOR EMERGENCY-SURVIVAL PRESSURE SUITS

In aviation and cosmonautics, the systems of technical devices which provide the necessary ambient conditions for normal human activity for both pressure suits and the cabins of airplanes, helicopters, and spacecraft are termed life support (conditioning) systems (LSS) [the term "conditioning" is used primarily in aviation while "life support" is used in cosmonautics and pressure suit design (Ed.)]. /55

These conditions are determined primarily by the pressure, temperature, humidity, and composition of the air in flight vehicle cabins and pressure suits, and also by several other factors which together ensure the operating efficiency and safety of the crews of all types of flight vehicles.

Under normal flight conditions, the physical parameters of the medium surrounding man are created and automatically maintained by the flight vehicle cabin life support system. The emergency-survival pressure suit (ESS) is used in case of failure or disruption of the operation of this system, and in case of forced egress from an airplane in flight.

The emergency-survival pressure suit, worn by the crew throughout the flight, determines to a considerable degree crewmember comfort.

Therefore, the operating efficiency of man during flight when using an emergency-survival suit is determined by the interaction of the flight vehicle (FV) cabin and pressure suit life support systems.

In order to reduce size, weight, and energy requirements, the life support systems for emergency-survival suits are functionally and structurally combined with the spacecraft cabin conditioning systems, while retaining complete autonomy under emergency conditions. Therefore, the configuration and operation of the ESS LSS must be examined in connection with the FV cabin LSS.

1. Physiological and Hygienic Conditions in FV Cabins

The LSS for flight vehicle pressurized cabins are subdivided into:

ventilated (atmospheric) cabins, in which pressurization and through-flow ventilation are provided by atmospheric air compressed in the gas turbine engine compressors;

regenerative (autonomous) pressurized cabins, with closed circulation and regeneration of the air being accomplished by special equipment.

The physical parameters of the air in FV cabins are established as a function of FV mission, flight altitude, and duration. The longer the flight duration, the smaller the deviations of these parameters from their optimum values must be. /56

It is desirable that the *air pressure* in airplane cabins with through-flow ventilation by compressed atmospheric air be maintained close to the pressure of atmospheric air at sea level; however, this is associated — on the one hand — with increase of the cabin weight because of the necessity for providing adequate cabin strength and — on the other hand — with the hazard of a pressure differential which is dangerous for man in the case of sudden loss of cabin pressurization.

On the basis of physiological tests and flight experience, it has been established that:

(a) in the cabins of passenger and transport airlines, the air pressure should be no less than 600 — 630 mm Hg, which corresponds to a cabin "altitude" of 1.5 — 2 km; in this case, there is no need to supply additional breathing oxygen;

(b) in the cabins of military airplanes, the air pressure is usually no less than 267 mm Hg (cabin "altitude" up to 8 km) for flight duration up to four hours and no less than 308 mm Hg (cabin "altitude" up to 7 km) for flight duration longer than four hours.

The *rate of air pressure change* in flight vehicle cabins during climb and descent is limited by the capability of the human organism to equalize the pressures in his semiclosed cavities (primarily in the middle ear cavity) with the pressure in the cabin.

The permissible rate of air pressure increase in the cabin during descent is considered to be as follows:

— for flights with duration up to two hours, the rate should be no more than 5 — 10 mm Hg/sec [8];

— for flights longer than four hours, the rate should be no more than 3 — 5 mm Hg/sec.

Usually air pressure decrease (during climb, for example) is withstood by man considerably easier than pressure increase; in this connection, the rate of pressure decrease may be approximately twice the rate of pressure increase.

The air pressure in pressurized airplane cabins varies with altitude as a function of airplane type and mission in accordance with the data shown in Figure 3.1.

In the pressurized cabins of Soviet spacecraft with closed regenerative ventilation systems, an oxygen-nitrogen atmosphere is maintained with air pressure on the order of 760 mm Hg and oxygen partial pressure about 160 mm Hg. The USA astronauts breathe pure oxygen with pressure 308 — 267 mm Hg (cabin "altitude" 7 — 8 km).

The use of an oxygen atmosphere makes the cabin considerably lighter (as a result of reduction of the design pressure in the cabin by a factor of 2.5 — 3) but is hazardous from the fire standpoint.

The *air temperature* in the cabins of all flight vehicle types should be in the limits of 20 — 22° C, brief (for 10 to 20 minutes) reduction of the temperature to 10° C, and increase to 30° C is permitted.

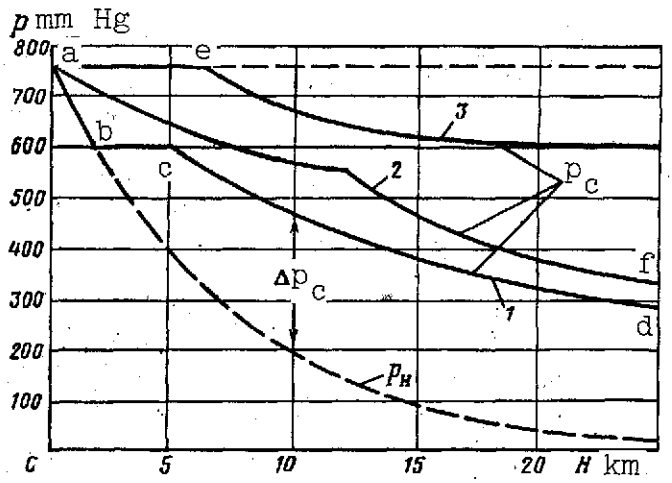


Figure 3.1. Typical air pressure regulation laws in pressurized airplane cabins.

H — flight altitude; p_H — atmospheric pressure at altitude H (in standard atmosphere); p_c — absolute cabin pressure; Δp_c — differential cabin pressure; $\Delta p_c = p_c - p_H$; 1 — fighters a — b ($p_c = p_H$), b — c (p_c = const), c — d (Δp_c = const); 2 — bombers with limited rate of cabin pressure change during climb; 3 — passenger and transport airplanes a — e (p_c = 760 mm Hg = const).

In an emergency situation, large variations of the cabin temperature are possible, depending on spacecraft construction, climatic conditions, and flight velocity.

The *relative humidity of the air* in the cabins of modern flight vehicles is not subject to strict regulation; the optimum value is assumed to be 40 — 60% and change from 15 to 70% is permitted.

Carbon dioxide and other contaminants. It has been established that the CO_2 partial pressure in flight vehicle cabins should be maintained at a level of no more than 2 — 6 mm Hg, and the maximum permissible value is usually taken to be 12 — 15 mm Hg. /57

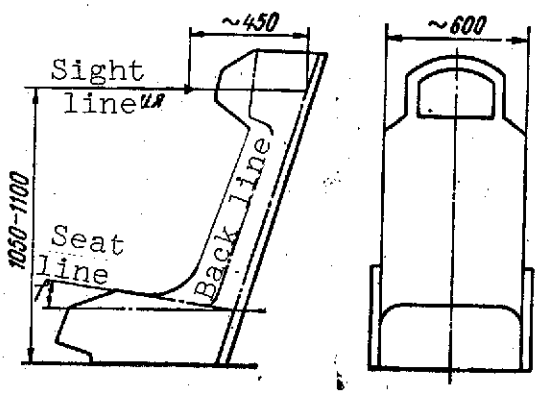


Figure 3.2. Possible ejection seat scheme.

The maximum permissible concentrations of other contaminants are shown in Table 4.1.

The *noise level* in flight vehicle cabins during flight should not exceed the values presented in Chapter 2. The noise level can be permitted to rise to 90 — 100 dB for short periods. When using earphone helmets, the cabin noise level can be permitted to increase by 10 — 15 dB.

The *seats* and *hatches* in flight vehicle cabins are of great importance for vehicle crew operating efficiency and safety.

Flight vehicle crewmembers are in definite fixed positions (working positions) in their work chairs practically throughout flight. Therefore, the working position of the flight vehicle crew is selected and established on the basis of maximum convenience in the use of all the controls in the cabin, optimum viewing field, and minimum fatigue.

Figure 3.2 shows a typical pilot ejection seat configuration.

For flight durations of more than 3 — 4 hours, the air plane seat design permits the pilot to increase the chair back tilt angle from 16 — 18° to 35° for relaxation.

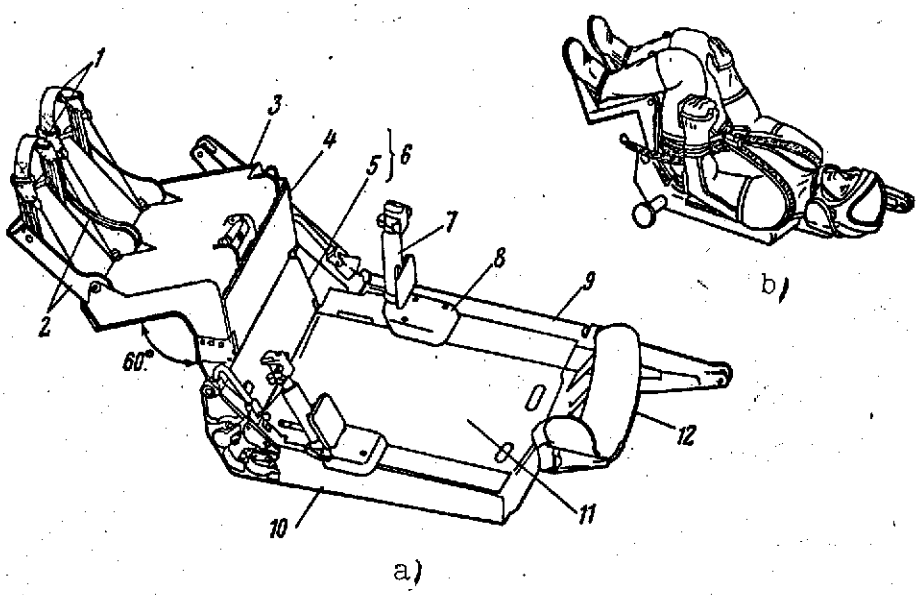


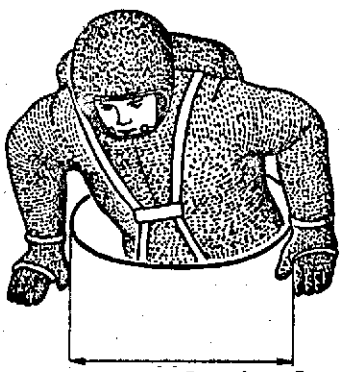
Figure 3.3. Cosmonaut seat.

a — general view of seat; b — position of cosmonaut in seat; 1 — restraining straps; 2 — foot support; 3 — leg support; 4 — thigh support; 5 — hip support; 6 — seat pan; 7, 8 — arm rests; 9 — side beam; 10 — back; 11 — back pan; 12 — headrest.

In contrast with the airplane seat, the seat in the spacecraft cabin must, first of all, provide the position of the individual in which he withstands most easily the g forces which arise during spacecraft launch and landing (Figure 3.3).

The dimensions of flight vehicle cabin hatches must be selected with consideration for crew clothing and equipment; hatch utilization convenience is verified on cabin mockups.

In the absence of differential pressure in his pressure suit, a man can utilize the hatches normally found in airplanes. /59



Diam. of circle or side of square 700 — 900 mm

Figure 3.4. Upper exit hatch for man in pressure suit.

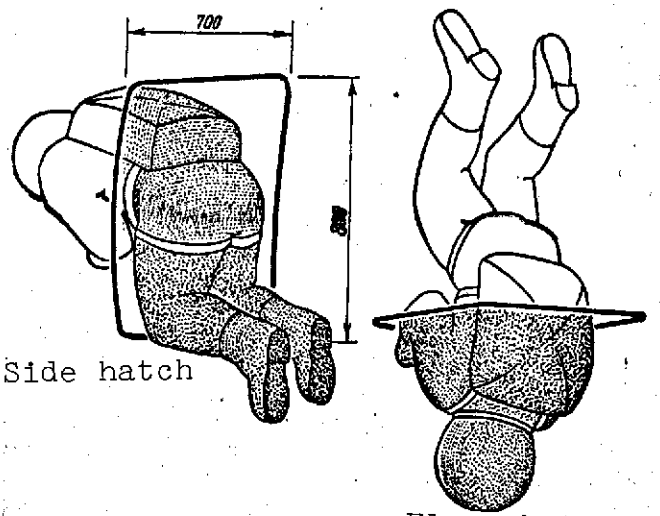


Figure 3.5. Side and bottom hatches for man in pressure suit.

The hatch dimensions for emergency egress from flight vehicles in a pressurized space suit (with differential pressure in the suit) are shown in Figures 3.4 and 3.5.

In arranging crew work stations, we must consider that the pressure suit (just as all other equipment) increases both man's weight and dimensions.

Table 3.1 shows some corrections to the male body dimensions which should be considered in arranging the equipment and seats in flight vehicle cabins (Figure 3.6).

2. Ventilation and Oxygen Supply Systems for Ventilated Emergency-Survival Pressure Suits /60

The LSS for emergency-survival pressure suits usually include:

TABLE 3.1

APPROXIMATE CORRECTIONS (ADDITIONS) TO MAN'S WEIGHT AND OVERALL DIMENSIONS AS FUNCTION OF HIS EQUIPMENT TYPE [3]

Change	Summer flightsuit	Winter flightsuit	Pressure suit	
			Unpressurized	Pressurized
Weight in kG	2.0—3.0	4—6	9—12	9—12
Head width, mm	50—70*	50—70*	100—150*	100—150
Distance from eye to crown, mm	—	—	25—50*	25—70
Shoulder width, mm	12	50—75	20—30	50—100
Hip width, mm	12	50—75	20—50	50—100
Elbow width, mm	12—20	50—90	50—90	100—200

*With helmet.

(1) system for supplying air from the conditioning system for pressure suit ventilation and pressurization;

(2) emergency system for supplying air to the pressure suit from bottles;

(3) line for ventilating the pressure suit from ground air conditioner;

(4) oxygen supply system.

In some airplanes, this system is supplemented by a line for supplying compressed air from the cabin air conditioning system into the g suit bladders.

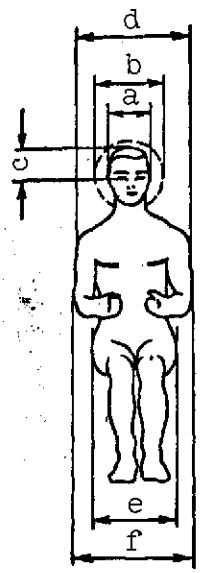


Figure 3.6. Change of male body dimensions as function of flight equipment.

a — head width; b — head width with pressure suit helmet; c — distance from eye line to top of head; d — shoulder width; e — hip width; f — elbow width.

Air Supply from Conditioning System for Pressure Suit Ventilation and Pressurization

The parameters (flowrate and pressure) of the air supplied from the conditioning system depend on the pressure suit design.

In the mask type pressure suit, the amount of air must be adequate for ventilation of the torso, helmet, and extremities in order to remove the moisture released by the organism.

In the non-mask type pressure suit, the amount of air supplied must be adequate to remove from the helmet the perspiration and respiration products released by the crewmember.

The heat production (energy expenditure) of a pilot (depending on flight complexity) amounts to 150 — 350 kcal/hour, and the oxygen usage for breathing and carbon dioxide elimination varies correspondingly.

In designing the system to supply air for pressure suit ventilation and pressurization, it is assumed that the pilot performs work of moderate intensity; in this case,

— the heat output is 4 kcal/min (240 kcal/h);

— moisture evolution from the skin surface and lungs is 3 g/min;

— carbon dioxide evolution is 0.65 g/min.

The following requirements are usually imposed on the air supply system:

— amount of air supplied ranges up to 400 liters(s)/min;

— air temperature at the suit inlet ranges from 10 to 80° C.

In order to ensure normal functioning of man in a pressure suit, it is necessary to maintain an absolute pressure of no less than 197 mm Hg under the suit shell (see Figure 2.3).

However, in those cases in which the pilot (or cosmonaut) was breathing air or a mixture of air and oxygen prior to the instant of cabin depressurization, an absolute pressure of no less than 308 mm Hg must be maintained in the pressure suit after cabin depressurization.

In practice, it is not always possible to create the optimum physiological conditions for the flyer in his pressure suit. This may occur in those cases when it is necessary to reduce to the maximum extent possible the differential pressure in the pressure suit in order to improve mobility or when the system cannot provide the specified pressure regime.

We present below a typical classification of the various differential pressure regimes in the pressure suit as a function of flight time, which must be considered very approximate and obviously will be refined as experience is accumulated in pressure suit use under various conditions.

A design "altitude" in the pressure suit of no more than 7 km (308 mm Hg or 0.4 kG/cm^2) is selected to provide protection against altitude sicknesses (see Chapter 2). /61

A limit working "altitude" in the pressure suit (197 mm Hg or 0.27 kG/cm^2) is selected to provide ground-level breathing conditions ($p_{O_2 alv}$ = 110 mm Hg).

A working "altitude" in the suit of 11 km (169 mm Hg or 0.22 kG/cm^2) is selected to provide the condition $p_{O_2 alv}$ = 82 mm Hg.

A maximum "altitude" in the suit for flight duration up to 15 minutes of 12 km (147 mm Hg or 0.19 kG/cm^2) is selected to provide $p_{O_2 alv}$ = 60 mm Hg.

Determination of Amount of Ventilating Air to Remove Water Vapor from the Pressure Suit

The air volume required for suit ventilation as a function of the specified relative humidity in the suit is determined from the well-known formula

$$W_m = \frac{g_{se}}{\varphi/100 (d - d_{in})} \qquad (3.1)$$

where g_{se} is the amount of moisture released by man in the form of sweat and with the exhaled air in g/h; φ — specified relative humidity in %; d — absolute moisture content with air saturation at the specified temperature in g/m^3; d_{in} — absolute moisture content of the air entering the suit in g/m^3.

The absolute moisture content of air is independent of pressure and is a function only of air temperature.

Example. The moisture evolution of the man is g_{se} = 180 g/h; dry air (d_{in} = 0) is supplied to the suit, the relative humidity of the air in the suit φ=50%.

The maximum moisture content of the air leaving the suit for t_{out} = 20° C (from Table A2) is d = 17.9 g/m³. Substituting these initial values into (3.1), we obtain

$$W_m = \frac{180}{\frac{50}{100} \cdot 17{,}9} = 20 \text{ m}^3/\text{h}.$$

Determination of Amount of Ventilating Air to Remove Exhaled Moisture from Helmet

According to the data of Table 2.4, when performing work of moderate intensity, the oxygen flowrate is 0.8 liters(s)/min and the pulmonary ventilation volume is 20 liters(s)/min (1.2 m³/h).

For complete moisture saturation of the exhaled air, we find from Table A2 that the maximum moisture content for 20° C is 17.9 g/m³ (17 mm Hg). Specifying φ = 60%, from (3.1), we determine the air quantity required to ventilate the helmet in order to remove the exhaled moisture

$$W_{mh} = \frac{17{,}9 \cdot 1{,}2}{\frac{60}{100}(17{,}9 - 0)} = 1.98 \text{ m}^3/\text{h}.$$

Determination of Amount of Ventilating Air to Remove Carbon Dioxide from Helmet

The calcualtion of the required fresh air flow to the helmet on the basis of permissible carbon dioxide partial pressure in the helmet is made using the formula

$$W_{cd} = \frac{T_{su} \cdot R_{cd}}{p_{cd \cdot per}}(g_{cd \cdot man} + g_{cd \cdot in}), \qquad (3.2)$$

where R_{cd} is the gas constant of carbon dioxide; T_{su} — air temperature in the suit in ° K; $p_{cd \cdot per}$ — permissible carbon dioxide partial pressure in the suit; $g_{cd \cdot man}$ — amount of carbon dioxide released by man in g/min; $g_{cd \cdot in}$ — amount of carbon dioxide present in the air entering the suit in g/min.

Example. The permissible carbon dioxide partial pressure in the pressure suit is $p_{cd \cdot per}$ = 15 mm Hg, the air temperature in the suit is T_{su} = 293° K, the carbon dioxide content in the air entering the suit is $g_{cd \cdot in}$ = 0.

For moderate physical workload, the amount of carbon dioxide released by man (for respiration coefficient 0.8) is $g_{cd \cdot in}$ = 0.65 liters(s)/min, for CO_2 specific weight γ = 1.98 g/liter(s), we find $g_{cd \cdot man}$ = 0.65 · 1.98 = 1.290 g/min.

The gas constant of carbon dioxide is R_{cd} = 19.27 kG/m/kG/°C = 192.7 dm/°C.

The permissible carbon dioxide partial pressure is: 1 mm Hg = 13.6 kG/m^2; $p_{cd \cdot in}$ = 15 mm Hg = 15 · 13.6 = 204 kG/m^2 = 2040 g/dm^2.

The amount of air supplied to the pressure suit required for removal of carbon dioxide from the suit is, using (3.2)

$$W_{cd} = \frac{192,7 \cdot 293}{2040} = 1.29 = 2.06 \text{ m}^3/\text{hr}.$$

Determination of Amount of Air Required to Maintain the Required Temperature in the Pressure Suit

In determining the amount of air necessary to maintain the required temperature in the pressure suit, we can assume that under normal conditions the cabin temperature is maintained at the level 20 — 22° C and under emergency conditions varies in the range from -20 to + 60° C.

The amount of heat which must be supplied to the pressure suit when the cabin temperature is negative can be obtained from the heat balance equation $Q_{in} = Q_{man} + Q_{hf}$, where Q_{man} is the amount of heat produced by the human organism in kcal/h, Q_{hf} is the amount of heat (thermal flux) coming through the pressure suit shell from outside.

To determine Q_{in}, we can use the equation

$$Q_{in} = Wc_p\gamma(t_{in}-t_{out})p_{su}/760, \qquad (3.3)$$

where W is the amount of air supplied in $m^3(s)/h$, $c_p = 0,241$ kcal/kG/°C — specific heat of air; $\gamma = 1.225$ kG/m^3 — specific weight of air under standard physical conditions (760 mm Hg, 15° C); t_{in} and t_{out} are, respectively, the air temperatures at the inlet to and outlet from the pressure suit.

Example. For air flow rate 18 m^3/h (300 liters(s)/min), t_{in} = 70° C and t_{out} = 35° C, Q_{in} = 18 · 0.24 · 1.225 · 35 = 185 kcal/h.

Consequently, the thermal resistance of the pressure suit must be such that the heat flux $Q_{hf} = Q_{in} - Q_{man}$.

The amount of heat which must be removed from the pressure suit in the case of high positive temperature in the cabin, in accordance with the heat balance equation, will be $Q_{cool} = Q_{man} + Q_{pen}$, where Q_{pen} is the heat flux penetrating from the cabin into the suit. /63

If we assume that the incoming air is heated to the temperature of the human body, then the heat transfer process will take place by perspiration evaporation.

Example. With air flow for suit ventilation W = 18 m^3/h, t_{in} = 20° C, and absolute moisture content of the incoming air d = 18 g/m^3 (see Table A2), the amount of perspiration which can be removed from the space inside the pressure suit will be g_s = 18 · 18 = 324 g/h. Assuming that the latent heat of evaporation of water (sweat) r = 580 kcal/kG, we obtain Q_{cool} = 0.324 · 580 = 224 kcal/h.

Emergency Air Supply

Emergency air flow must be activated automatically upon termination of air supply for pressure suit ventilation from the air conditioning system (Figure 3.7).

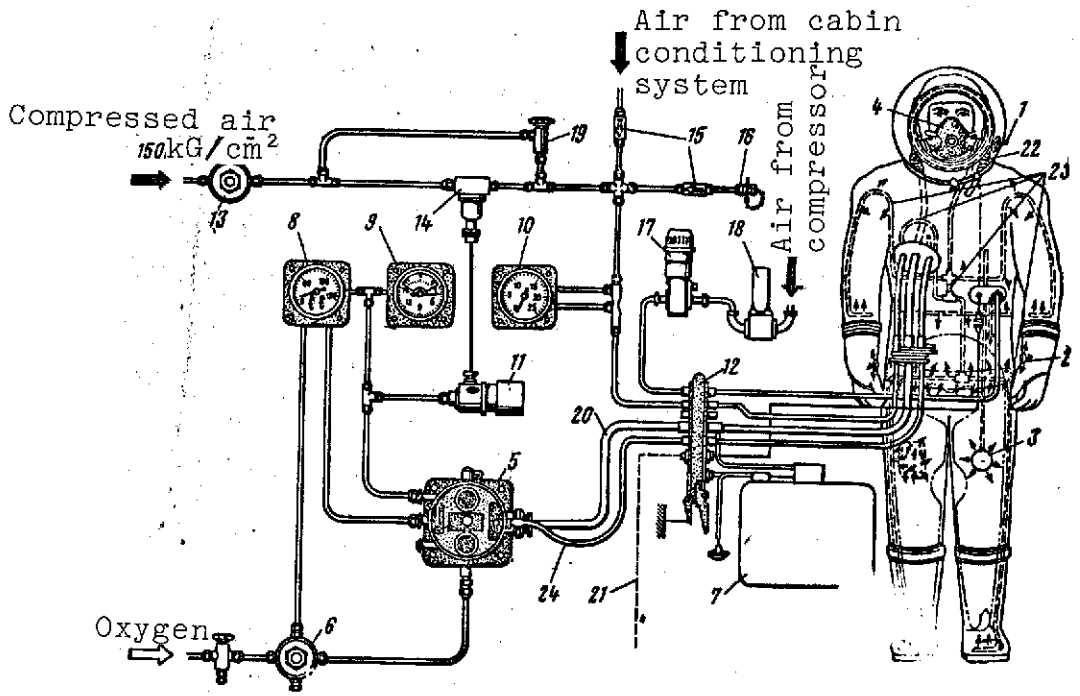


Figure 3.7. Life support system of mask-type ventilated emergency survival pressure suit.

1 — helmet air discharge valve; 2 — glove air discharge valve; 3 — suit pressure regulator; 4 — oxygen mask; 5 — ship's demand-type oxygen regulator; 6 — oxygen pressure reducer; 7 — parachute oxygen regulator; 8 — oxygen flow indicator and pressure gage; 9 — pressure suit "altitude" indicator; 10 — ventilation air flow indicator; 11 — dangerous pressure suit "altitude" warning indicator; 12 — single point pressure suit line disconnect; 13 — emergency air flow pressure reducer; 14 — emergency air flow controller; 15 — check valve; 16 — airframe fill fitting; 17 — g-suit pressure controller; 18 — g-suit filter; 19 — valve for manual activation of emergency air flow; 20 — oxygen hose; 21 — communications lead; 22 — exhalation hose; 23 — pressure suit ventilation system; 24 — equalizing hose.

The flow volume must be adequate and must maintain the specified differential pressure in the pressure suit and ventilation of the helmet in order to remove the respiration products (moisture and carbon dioxide).

The emergency air supply operating time must be adequate for the flight vehicle to descend to an altitude of 4 km, at which the helmet faceplate can be opened.

Ground Ventilation Line

/64

The flightline pressure suit ventilation line is activated when the pilot is on alert in the airplane on the airfield and is intended for pressure suit ventilation. The temperature of the air supplied will vary from 10 to 80° C, depending on the ambient temperature (±50° C). The flow volume varies from 100 to 400 liters(s)/min.

Oxygen Supply System

The oxygen supply system is designed to supply (breathing) oxygen in case of disruption of the cabin atmosphere gaseous composition and also when the pilot leaves the flight vehicle under emergency conditions.

The pressure suit oxygen supply system consists of the ship's oxygen system, parachute oxygen system, oxygen mask (in the mask type-variant), monitoring and metering equipment, and the oxygen supply (gaseous or liquid).

Figure 3.7 shows a possible mask-type ventilated pressure suit life support system. The oxygen necessary for breathing is supplied to the mask from the oxygen regulator 5. The helmet, torso, and extremities are ventilated by air coming from the cabin conditioning system.

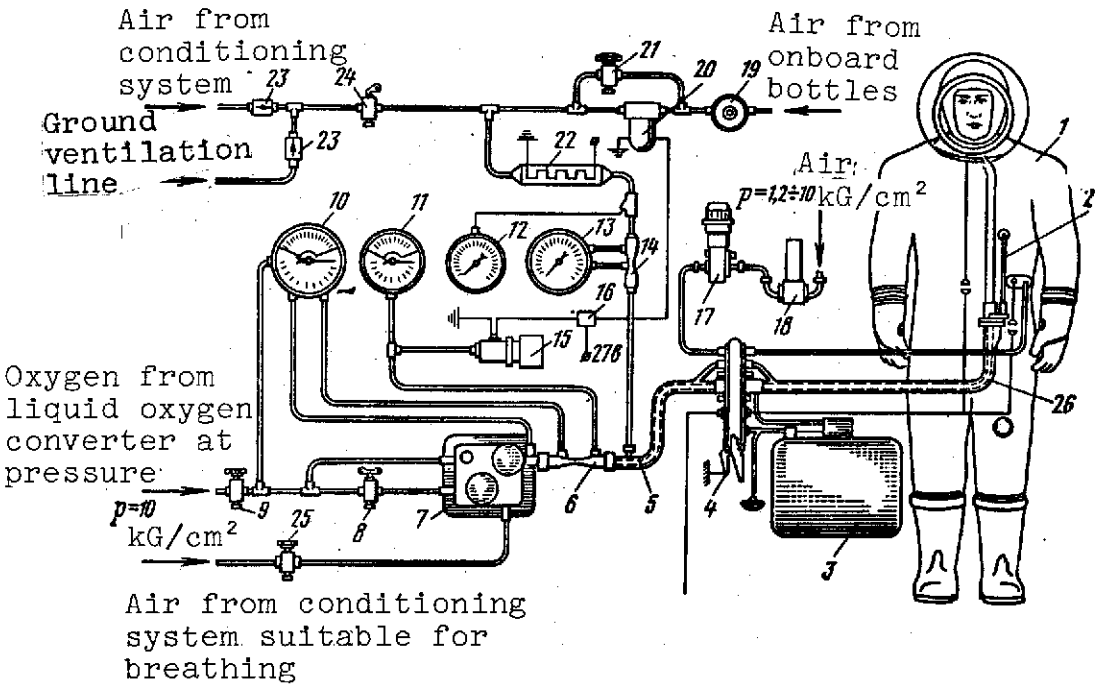


Figure 3.8. Life support system of non-mask type ventilated emergency survival pressure suit.

1 — pressure suit; 2 — ventilating air hose; 3 — parachute oxygen system; 4 — single point pressure suit line disconnect; 5 — oxygen hose (located inside the hose 2); 6 — oxygen flow indicator Venturi tube; 7 — ship's continuous flow oxygen regulator; 8 — emergency oxygen supply valve; 9 — oxygen supply on-off valve; 10 — oxygen flow indicator and pressure gage; 11 — suit "altitude" indicator; 12 — temperature indicator of air supplied to the pressure suit; 13 — flow indicator for this air; 14 — Venturi tube of this indicator; 15 — dangerous pressure suit "altitude" warning indicator; 16 — signal lamp of this warning indicator; 17 — g-suit pressure controller; 18 — g-suit filter; 19 — emergency air flow pressure reducer; 20 — emergency air flow controller; 21 — emergency air flow manual activation valve; 22 — air preheater; 23 — check valve; 24 — ventilating air flow on-off valve; 25 — breathing air flow on-off valve; 26 — ventilating air hose, inside which the oxygen supply hose is located.

The non-mask-type pressure suit oxygen supply system is shown in Figure 3.8. The oxygen coming from the oxygen regulator does not ventilate a mask but rather the entire helmet, which is separated from the pressure suit shell by a neck dam

through which the exhaled air and the oxygen not used for breathing are exhausted from the helmet into the pressure suit shell. Just as in the mask type version, the pressure suit shell is ventilated by air from the cabin conditioning system. /65

The use of the oxygen mask provides several advantages in comparison with the oxygen supply system without a mask, namely:

(a) the breathing oxygen flowrate is reduced considerably;

(b) internal fogging of the helmet is avoided, since the exhaled air is discharged from the mask and helmet through a special hose into the pressure suit shell and does not impinge on the helmet glass;

(c) the possibility is provided for continuing flight if helmet pressurization is lost even with an "altitude" in the cabin up to 12 km.

But the oxygen mask restricts head movement and irritates the skin when used for long periods.

The most complex and critical components of the oxygen supply system are the ship's and parachute oxygen regulators.

The emergency-survival pressure suit life support systems utilize stationary oxygen regulators installed aboard the flight vehicle or directly on the pressure suit helmet, and parachute oxygen regulators which supply oxygen in case of emergency egress from the flight vehicle or in case of stationary oxygen regulator failure.

The stationary oxygen regulators must satisfy the following basic requirements:

— automatic regulation of volumetric oxygen content in the inhaled air as function of altitude (see Figure 2.2);

— minimum respiration resistance;

— required oxygen flowrate;

— operational simplicity.

The oxygen regulators may provide continuous, periodic, and combined (continuous and periodic) oxygen flow.

The regulators with continuous oxygen flow are simple in operation and reliable, but are not economical since the oxygen coming from the regulator during exhalation is not utilized. The oxygen flowrate is calculated from the condition of pulmonary ventilation with moderate workload, in view of which excess oxygen flow is provided in the low physical workload case.

The oxygen flowrate in these regulators is controlled by an oxygen pressure reducer with metering device (orifice) or capillary tube.

At the present time, continuous oxygen flow is used in the ship's oxygen system on passenger airplanes and in parachute systems.

In the oxygen regulators with pressure reducer, the oxygen flow may be constant with altitude change or may be increased or decreased by an aneroid device. In regulators with capillary tube in place of the pressure reducer, the oxygen flowrate decreases in the course of time.

Regulators with periodic oxygen flow operate under the influence of the pressure reduction which develops in the pressure suit mask or helmet during inhalation.

The regulator operates as follows (Figure 3.9). During inhalation, reduced pressure develops in the mask and in the internal (below the membrane) regulator cavity, and under the influence of this reduced pressure the membrane 1 deflects and rotates the lever 2, opening the valve 4. Now oxygen enters the regulator and then flows through the nozzle 6 and injector diffuser 12 and hose to the mask 17. Upon termination of inhalation, the pressure reduction in the mask and regulator disappears, the membrane 1 and lever 2 return to their original /66
positions, valve 4 closes under the influence of the spring 3, and oxygen flow into the mask terminates. During exhalation, a positive pressure is created in the mask, the inhalation valve 18 closes, and the exhaled air can discharge through the exhalation valve 19.

It follows from this discussion that, in this regulator, oxygen flow takes place only during inhalation and in a quantity proportional to the pressure reduction in the regulator, i.e., proportional to inhalation depth.

Up to altitudes of 8 — 9 km, the regulator feeds a mixture of oxygen and air to the mask. Air inflow takes place with the aid of an injector in which the oxygen flow energy which arises during inhalation is utilized, and is regulated as a function of altitude by the aneroid stack 10.

Thus, at an altitude of 4 km, the oxygen content (by volume) is 35 — 55%, at an altitude of 7.5 km it is 55 — 92%, and at an altitude of 8.5 km it is 90% and more.

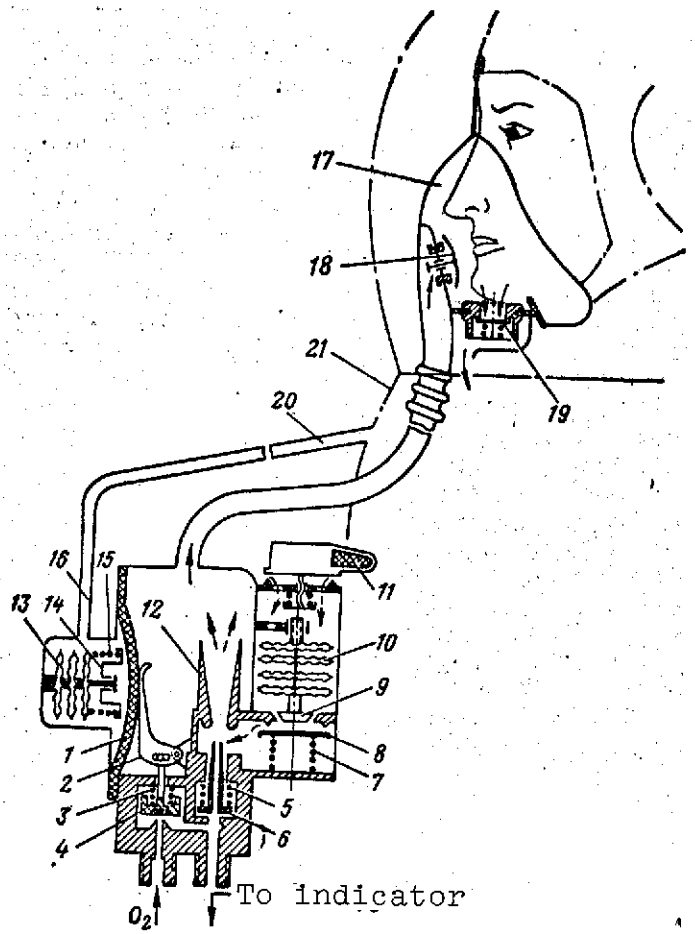


Figure 3.9. Schematic of oxygen regulator with periodic oxygen flow (demand controller type).

1 — membrane; 2 — lever; 3, 5, 7, 15 — springs; 4 — oxygen valve; 6 — injector nozzle; 8 — check valve; 9 — air inflow valve; 10 — aneroid stack; 11 — manual air inflow switch; 12 — injector diffuser; 13 — differential pressure mechanism aneroid stack; 14 — cap; 16 — fitting (communicates with atmosphere or is connected with pressure suit shell); 17 — oxygen mask; 18 — (rubber) inhalation valve; 19 — (mica) exhalation valve; 20 — equalizing hose; 21 — pressure suit shell.

In those cases when it is necessary to provide pure oxygen for breathing, for example during desaturation, air inflow is positively shut off by the manual switch 11.

In case of poor mask fit to the face and head, the oxygen flow may diminish because of air inflow under the mask from the surrounding space and the associated decrease of the pressure reduction in the regulator. At high altitudes in the case of oxygen deficiency, a syncopal state may occur suddenly. This phenomenon is prevented by a differential pressure mechanism (13, 14, and 15), which creates at altitudes above 4 km a small differential pressure (30 — 40 mm H_2O) in the regulator and in the mask, as a result of which air inflow into the mask is precluded. /67

The resistance developed by the regulator during inhalation depends on the pulmonary ventilation magnitude (the lower this value, the easier breathing is), therefore, it is desirable that this value not exceed 15 — 20 mm H_2O.*

In modern demand-type oxygen regulators, this magnitude of the inhalation resistance is provided only with pulmonary ventilation 7.5 — 15 liters/minute. With pulmonary ventilation on the order of 30 liters/minute, the inhalation resistance at sea level reaches 60 — 70 mm H_2O. This resistance impedes breathing and tires the individual. With altitude increase, both the density of the oxygen-air mixture supplied by the regulator and the inhalation resistance decrease (Figure 3.10).

*The respiration resistance of oxygen regulators is the maximum pressure reduction or differential pressure which the individual must create in the oxygen system mask during inhalation and exhalation in order to overcome the hydraulic resistances along the inhaled-exhaled air path.

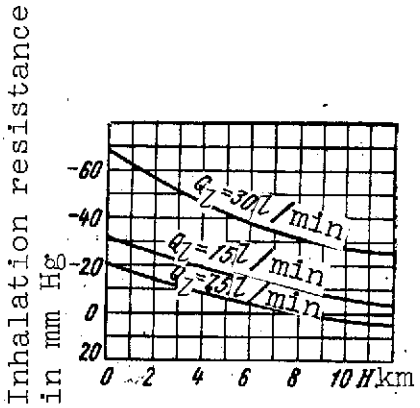


Figure 3.10. Typical variation of continuous flow oxygen regulator inhalation resistance with flight altitude and man's pulmonary ventilation [2].

The inhalation resistance of the oxygen regulator itself (membrane, lever, and oxygen valve with spring) amounts to no more than 50% of the overall resistance created by the entire system, including the ship's hoses, connectors, and oxygen mask.

Of no less importance in the respiration process is the resistance of the regulator to exhalation, which — depending on the pulmonary ventilation magnitude — varies at sea level in the range from 20 to 40 mm H_2O, and also decreases with altitude.

In regulators used in the pressure suit life support system, the cavity above the membrane must be connected by an equalizing hose with the suit shell. Otherwise, the differential pressure in the suit is transmitted into the regulator cavity below the membrane and does not permit the individual to create in this cavity the pressure reduction required to open the oxygen valve 4 and the check valve 18, i.e., it does not permit inhalation.

Regulators with combined oxygen flow are intended for operation in the non-mask system and combine in themselves the low respiration resistance and pressure change in the helmet during inhalation and exhalation which is characteristic of the continuous flow oxygen regulators and also the capability of supplying oxygen "on demand" for any workload, which is characteristic of the regulators with periodic oxygen flow.

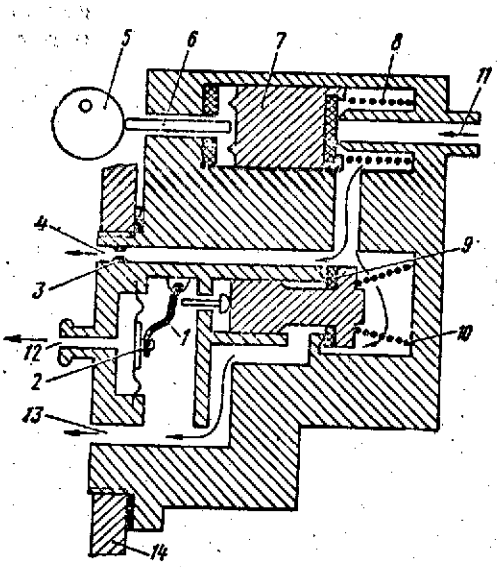


Figure 3.11. Schematic of (hypothetical) combined oxygen flow regulator.

1 — demand controller lever; 2 — demand controller membrane; 3 — orifice; 4 — line for continuous oxygen flow to helmet; 5 — eccentric for activating oxygen flow to regulator; 6 — plunger; 7 — continuous oxygen flow valve; 8 — spring; 9 — periodic oxygen flow valve; 10 — spring; 11 — oxygen flow from bottle; 12 — compensating hose; 13 — line for periodic oxygen flow to helmet; 14 — helmet shell.

The continuous oxygen flow in this regulator amounts to 15 to 20 liters(s)/minute and flushes the carbon dioxide from the helmet in the moderate physical workload case. With increase of the pulmonary ventilation, the pressure in the oxygen feed line decreases and the demand controller provides additional oxygen flow.

A schematic of the combined oxygen flow regulator is shown in Figure 3.11. The regulator is mounted directly on the pressure suit helmet. The regulator is automatically deactivated when the helmet faceplate is opened and is automatically activated and begins to operate when the faceplate is closed. /68

Activation of the regulator takes place with rotation of the eccentric 5, releasing the plunger 6 which had been held against the valve 7 by the eccentric. Under the influence of oxygen pressure and the spring 8, the valve 7 opens, then the seat on the valve seals the gap between the plunger and 6 and the case tightly. In this valve position, oxygen is supplied continuously through the orifice 3 to the pressure suit helmet.

The amount of oxygen flowing through the orifice 3 depends on the magnitude of the oxygen pressure at the regulator inlet and the orifice diameter.

The differential pressure ahead of the orifice is maintained constant by a separate pressure reducer.

Upon pulmonary ventilation increase to 30 liters/minute or more, the demand controller comes into operation whose cavity above the membrane is connected with the pressure suit shell by passage 12, while the cavity below the membrane is connected with the helmet by passage 13. The demand controller operates just like the regulator shown in Figure 3.9.

Figure 3.12 shows a pressure suit life support system which has a combined oxygen flow regulator. The regulator is mounted directly on the pressure suit helmet, which permits reducing the diameter of the oxygen hose (its resistance is overcome by the comparatively high pressure at the pressure reducer outlet — up to 2 — 4 kG/cm^2) and avoids the need for use of an equalizing hose (see Figure 3.7).

In this oxygen regulator, oxygen flow is provided either through a pressure reducer or bypassing the reducer (in emergency cases).

For servicing convenience, reducing flight preparation time, and simultaneous disconnect of all the emergency survival pressure suit lines during ejection, use is made of a single point connector.

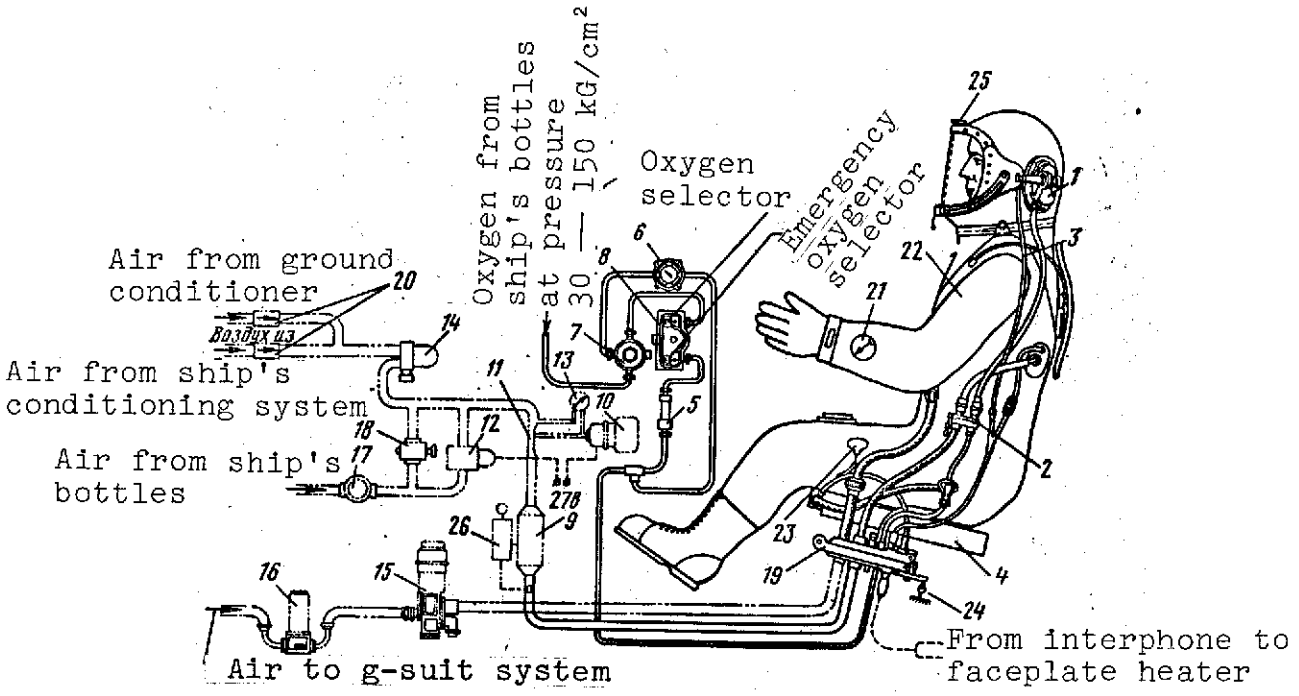


Figure 3.12. Possible emergency survival pressure suit life support system with combined oxygen flow.

1 — oxygen regulator; 2 — hose disconnect; 3 — helmet faceplate electric heater lead; 4 — parachute oxygen system; 5 — constant oxygen flow indicator; 6 — periodic oxygen flow indicator; 7 — oxygen pressure reducer; 8 — regulator control panel; 9 — air preheater; 10 — dangerous "altitude" warning indicator; 11 — air flow indicator Venturi tube; 12 — emergency air flow controller; 13 — air flow indicator; 14 — air flow regulator; 15 — g-suit filter; 16 — g-suit pressure controller; 17 — emergency air flow pressure reducer; 18 — manual valve; 19 — single point line disconnect on ejection seat; 20 — air lines; 21 — pressure gage; 22 — pressure suit; 23 — manual activation of oxygen flow from parachute system; 24 — lanyard attaching lower half of single point disconnect to airplane structure (floor); 25 — air inflow valve; 26 — temperature sensor.

The parachute oxygen regulators are individual-use regulators which supply the pilot with oxygen when ejecting from the airplane and descending by parachute.

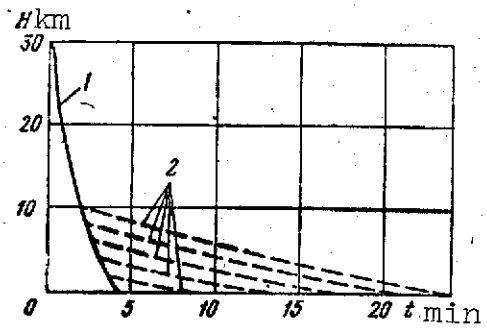


Figure 3.13. Pilot time of fall without parachute opening (1) and parachute descent time with opening at various altitudes (2).

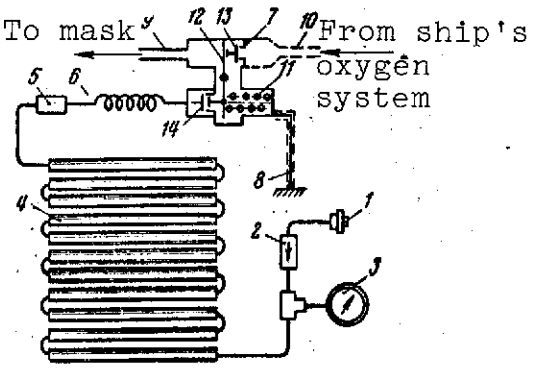


Figure 3.14. Schematic of KP-23 parachute oxygen system.

1 — fill fitting; 2 — check valve; 3 — pressure gage; 4 — small bottle with compressed oxygen; 5 — filter; 6 — capillary tube; 7 — oxygen supply disconnects; 8 — lanyard; 9 — hose from oxygen mask (pressure suit helmet); 10 — hose from ship's oxygen system and fall-away part of switch (dashed); 11 — spring; 12 — lever; 13 — check valve; 14 — oxygen valve.

The amount of oxygen supplied by the parachute oxygen regulator must be adequate not only for breathing, but also for maintaining a differential pressure under the pressure suit shell. The oxygen supply must be based on the time required for descent to an altitude which can be maintained without additional oxygen flow. /69

Figure 3.13 shows pilot fall time without parachute opening (curve 1) and parachute descent time (curve 2).

The oxygen supply is slected as a function of pressure suit type (with or without mask) and the specified time of descent to altitudes at which atmospheric air inflow begins and oxygen flow is terminated.

A schematic of the Soviet KP-23 parachute oxygen system is shown in Figure 3.14. The system is enclosed in a metal box

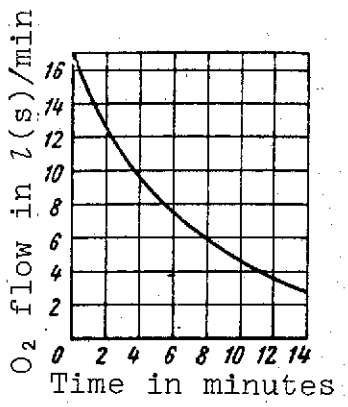


Figure 3.15. Oxygen flow versus time for KP-23 system.

of dimensions 360 x 290 x 23 mm. The 0.825 liter oxygen supply* is contained in 12 small bottles connected in series. The capillary tube 6 with internal diameter 0.35 mm serves to reduce the oxygen pressure. The tube length is selected so that, upon activation of the system, the initial oxygen flowrate will be 13 — 17 liters(s) per minute (Figure 3.15).

In case of emergency egress from the airplane, the parachute system lanyard — attached to the cabin floor — is pulled and withdraws the separator pins on the disconnect 7, the ship's oxygen system hose 10 is disconnected by the strong spring 11 and the lever 12, the opening which is thus formed is blocked by the valve 13, at the same time the oxygen valve 14 opens and oxygen flow to the mask or helmet begins. /71

The K-27m parachute oxygen system is equipped with an additional small bottle which provides augmented oxygen flow to the mask or helmet when it is activated. This system is used only together with the single point disconnect (see Figure 3.12).

The KP-27m system weighs no more than 5.3 kG and the overall dimensions are 360 x 260 x 35 mm.

*The oxygen supply at standard pressure and temperature is 123.75 liters.

In the pressure-reducer-type parachute systems, the pressure of the oxygen coming from the bottle is reduced to 3 — 6 kG/cm^2. Usually an orifice is installed at the outlet of the pressure reducer to ensure the required constant oxygen flow-rate (no less than 3 — 5 liters(s)/min).

The required oxygen supply is contained in a small cylindrical bottle at a pressure of 200 — 250 kG/cm^2. The system is activated manually by a cable mechanism.

The oxygen mask is intended for direct oxygen supply to the individual's breathing organs and must:

— cover the nose and mouth simultaneously without hindering breathing;

— fit tight to the face and not shift during accelerations;

— not interfere with conversation when using radio equipment;

— not interfere with vision nor restrict head movement;

— not cause discomfort during prolonged use;

— have low resistance of the inhalation and exhalation valves.

Masks are made in several sizes to provide good fit to the face.

A conventional oxygen mask can be seen in Figure 3.9. It consists of the rubber body 17, convoluted hose connecting the mask with the oxygen regulator, and the inhalation 18 and exhalation 19 valves.

The mask resistance to exhalation is determined by the construction of its exhalation valve and depends on pulmonary ventilation magnitude; under sealevel conditions and moderate intensity workload, it does not exceed 30 — 40 mm H_2O. This valve is usually made from mica to prevent adhesion by freezing.

Masks for pressure suits (see Figure 3.7) differ from the conventional masks in that they have a second convoluted hose through which the exhaled air is exhausted into the pressure suit shell and a food intake valve (see Figure 5.31).

The oxygen flowrate in the pressure suit LSS is of considerable importance, since the oxygen supply determined by this flowrate is stored in the compressed or liquified state in vessels of considerable weight and size.

In *the non-mask system* (see Figure 3.8), the oxygen flowrate is selected to maintain the carbon dioxide partial pressure at the required level in the exhaled air (in the helmet). The oxygen flowrate required to do this can be calculated using (3.2).

Usually we take W_{cd} = 40 — 50 liters/min (Figure 3.16).

When ventilating the helmet with oxygen, its flowrate from the regulator in liters(s) at various altitudes is calculated from the equation

$$W_{cd(H)} = W_{cd} \frac{p_H}{p_0}, \qquad (3.4)$$

where p_H is the air pressure at the altitude H; p_0 — air pressure at sea level (760 mm Hg).

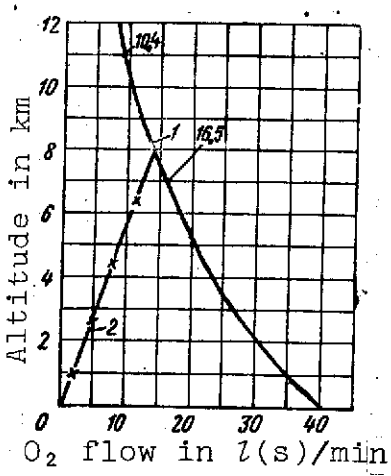


Figure 3.16. Oxygen flow versus altitude in non-mask type ventilated pressure suit.

1 — with pure oxygen flow (40 liters/min) into helmet for breathing; 2 — with use of oxygen-air mixture for breathing (pure oxygen is supplied at an altitude of 8 km).

For example, the oxygen flow in liters(s) at the height H = 10 km (p_H = 198 mm Hg) is /72

$$W_{cd(H)} = \frac{198}{760} 40 = 10{,}4.$$

To reduce to oxygen flowrate at altitudes up to 8 km, the helmet can be ventilated by an oxygen-air mixture if we provide in this case both the total mixture quantity necessary for carbon dioxide removal and the volumetric oxygen content ξ_H in the mixture required for the given altitude (see Figure 3.16).

In this case, the required oxygen flowrate from the regulator is

$$W_{ox(H)} = W_{cd} \frac{p_H}{p_0} \frac{\frac{ox.req}{100} - 0.21}{0.79}. \qquad (3.5)$$

In the mask-type system with periodic oxygen flow, its rate depends on the "altitude" in the cabin (pressure suit) and the physical workload. In this case, when breathing pure oxygen at altitudes above 8 km, the oxygen flowrate is

$$W_{ox(H)} = W_{pv} \frac{p_H}{p_0}. \qquad (3.6)$$

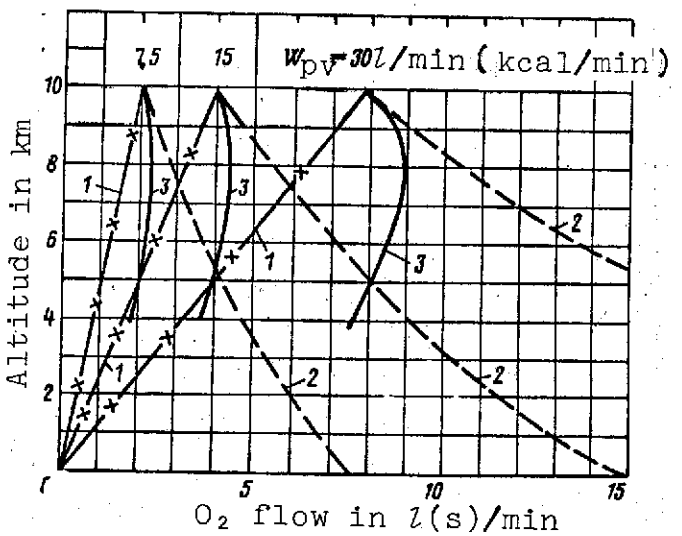


Figure 3.17. Oxygen flowrate in mask type ventilated pressure suit versus altitude for different pulmonary ventilations.

1 — theoretically required oxygen flow with air inflow; 2 — theoretically required oxygen flowrate when breathing pure oxygen; 3 — actual oxygen flowrate.

The magnitude of the pulmonary ventilation W_{pv} as a function of energy expenditure is shown in Table 2.4.

An oxygen-air mixture is provided by the regulator up to an altitude of 8 km; at altitudes above 8 km air inflow into the regulator terminates and pure oxygen is used for breathing.

The oxygen flowrate with air inflow is found from (3.5) with replacement therein of W_{cd} by W_{pv}.

The theoretically required oxygen flowrate with and without air inflow for various pulmonary ventilations is shown in Figure 3.17.

For various reasons the air inflow regulator (see Figure 3.9) cannot provide precisely the required oxygen-air mixture composition at various altitudes; therefore, the actual oxygen flowrate in the regulator with air inflow exceeds somewhat the theoretically required value. /73

If we assume that about 4% of the oxygen inhaled is utilized during breathing, then the pulmonary ventilation W_{pv} = 7.5 liters(s)/min will correspond to a heat output of 1.5 kcal/min.

3. Life Support System for Regenerative Emergency-Survival Pressure Suit

Regenerative cabins are used on flight vehicles intended for flight at high altitudes, where the atmospheric pressure is so low that it is impossible in practice to provide pressurization and ventilation of the cabin by compressed atmospheric air.

Usually the life support systems in regenerative cabins are constructed so that, under normal flight conditions, they maintain the specified microclimate parameters and provide suit ventilation. If an emergency situation arises, the pressure suit is automatically disconnected from the flight vehicle system and the autonomous energy life support system is activated, which provides the crewman with oxygen and removes the carbon dioxide and moisture released by him.

In designing life support systems for the regenerative emergency survival pressure suit, we again assume that the individual performs work of moderate intensity (see Table 2.4); in this case, the oxygen requirement amounts to 0.8 liters/min,

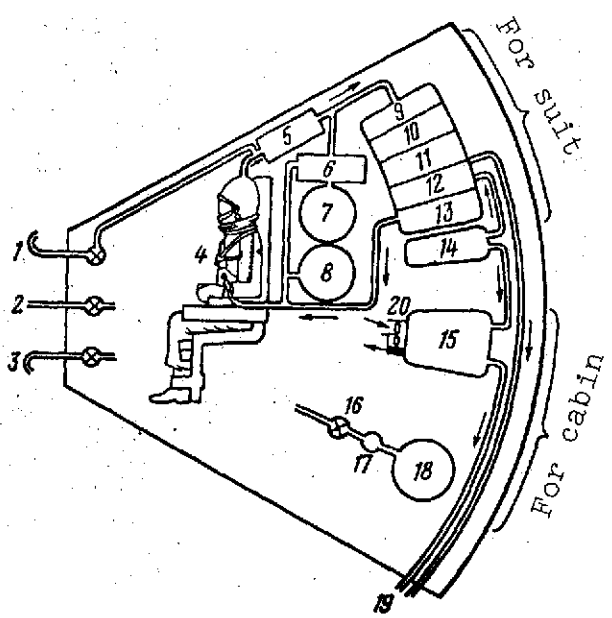


Figure 3.18. Schematic of life support system of American Mercury program spacecraft with regenerative pressurized cabin.

1 — air inlet valve; 2 — air outlet valve; 3 — safety valve; 4 — pressure suit; 5 — dust collector; 6 — oxygen flow regulator; 7 — oxygen (1.8 kG) bottle; 8 — emergency oxygen (1.8 kG) bottle; 9 — fan; 10 — odor absorber (activated charcoal); 11 — LiOH carbon dioxide absorber; 12 — pressure suit heat exchanger; 13 — water separator; 14 — vessel with water supply; 15 — cabin heat exchanger; 16 — valve; 17 — regulator; 18 — oxygen supply bottle; 19 — water vapor overboard discharge from heat exchanger; 20 — cabin fan.

heat output is 4 kcal/min, moisture generation is 3 g/min, carbon dioxide generation is 0.65 liters/min.

The maximum permissible "altitude" in the suit is determined from the condition p_{O_2} = 197 mm Hg.

On this basis, the pressure in the pressure suit must be 0.26 kG/cm^2, which corresponds to a suit "altitude" of 10 km.

The possible technical solutions for such systems can be illustrated using the systems of the American Mercury, Gemini, and Apollo program spacecraft.

The life support system for the Mercury spacecraft is shown in Figure 3.18. It is designed to operate for 28 hours and has the following characteristics:

— cabin atmosphere, oxygen;

— differential pressure, 258 ± 26 mm Hg;

— O_2 partial pressure, 241 ± 33 mm Hg;

— CO_2 partial pressure, from 0 to 26 mm Hg.

The temperature in the cabin is regulated manually and automatically in the range 10 — 20° C with the aid of the evaporative water heat exchanger 15 and the cabin fan 20.

The pressure suit in this system is intended only to protect the individual in case of cabin depressurization. Under normal flight conditions, no differential pressure is developed in the suit and the pilot breathes cabin air through the open helmet.

The spacecraft design provides for landing with the astronaut inside on the water only. Ejection of the astronaut from the spacecraft is not provided.

The gases are directed from the pressure suit into the dust collector 5 for removal of the dust and solid particles suspended in the gases. After addition of oxygen from the bottle 7, the gas stream is fed by the fan 9 (with electric motor) to the odor absorber 10 and CO_2 absorber 11, and then to the heat exchanger 12 for cooling to temperature +5° C.

After cooling, the gases (mixture of oxygen and water vapor) pass through the water separator 13 in which the condensate which forms as water drops is absorbed by a sponge. The continuous closed circulation of the gases in the system provides complete regeneration and maintains the specified microclimate conditions in the pressure suit. /74

Oxygen loss through cabin leakage is compensated by oxygen flow from the supply bottle 18.

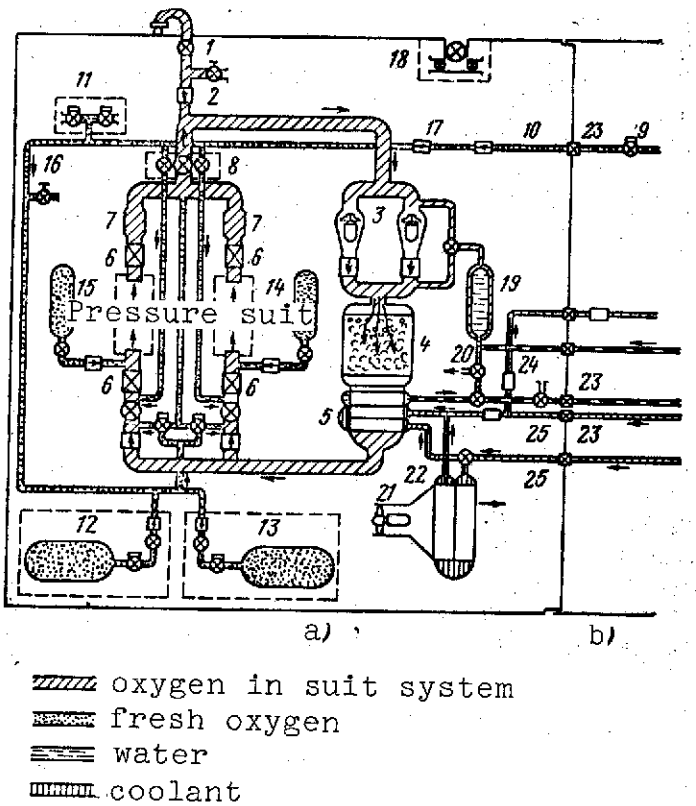


Figure 3.19. Schematic of life support system of American Gemini program spacecraft.

a — command module (reentry vehicle); b — support module; 1, 2 — suit pressure dump valves; 3 — fans; 4 — CO_2 and contaminant absorber; 5 — suit heat exchanger with water separator; 6 — suit disconnects; 7 — liquid trap; 8 — valves; 9 — pressure reducer in main oxygen supply line; 10 — oxygen flow line; 11 — cabin pressure regulator; 12, 13 — auxiliary oxygen supply vessels; 14, 15 — emergency oxygen bottles; 16 — cabin pressurization valve; 17 — check valve; 18 — cabin pressure bleed valve; 19 — drinking water vessel; 20 — drinking water flow valve; 21 — cabin fan; 22 — cabin heat exchanger; 23 — disconnects; 24 — water pump valve; 25 — coolant flow line.

Another technical solution of the regenerative life support system is shown in Figure 3.19.

This system performs the following functions:

— removal of respiration products from the cabin (command module) gaseous medium;

— maintain the cabin pressure and temperature in specified limits;

— water supply for crewmembers;

— pressurization and ventilation of the pressure suits.

The cabin atmosphere is oxygen. The pressure in the cabin is maintained at 271 mm Hg (cabin "altitude" about 8 km). The main oxygen supply is contained in liquid form in a gasifier in the support module at supercritical pressure (about 60 kG/cm^2), additional oxygen in the gaseous state is provided in the command /75 module in bottles 12 and 13 at 350 kG/cm^2 pressure. The (breathing) oxygen flowrate is 30 g/h per man.

After separation of the support module (during descent), the oxygen supply in the command module is provided from bottles 12 and 13.

The air temperature in the cabin is maintained at the specified level (about 26° C) by the heat exchanger 22, fan 21, and cooling system components located in the support module. The coolants used are water and a siloxane liquid which transports heat from the cabin to an external radiator.

The electrical energy to supply the onboard systems is generated by oxygen-hydrogen fuel cells, located together with the liquified oxygen and hydrogen supplies necessary for their operation in the support module. The water which forms in the fuel cell operating process enters the common water supply system.

Circulation of the gaseous medium in the pressure suit system is accomplished by the fans 3. Absorption of the odors and carbon dioxide from the gas takes place in the canister 4, filled with activated charcoal and lithium hydroxide. After removal of the contaminants, the still-moist oxygen enters the heat exchanger 5 for cooling, and here the moisture present in the gas is condensed and collected in the tank 19. /76

In case of pressure reduction in the cabin to 0.27 kG/cm^2, the suits are isolated from the cabin atmosphere and a differential pressure is created in the suits. In this case, oxygen supply to the suits, purification of the gaseous mixture leaving the suits, and temperature regulation take place just as they did prior to loss of cabin pressure.

The gaseous emergency oxygen supply is located beneath the ejection seats in the bottles 14 and 15, each containing 136 grams of oxygen at 239 kG/cm^2 pressure. During ejection, oxygen flow from these bottles is activated automatically and regeneration and temperature regulation in the pressure suits are terminated.

The life support system as a whole is designed for a 14-day flight of two astronauts and weighs (without considering the food supply weight) 193 kG.

4. Combined Systems for Oxygen Supply and Suit Ventilation

Combined life support systems were used in the Vostok and Voskhod spacecraft, which have regenerative cabins and ventilated suits.

These spacecraft have a primary life support system for the cabin and a suit life support system [4].

The primary system maintains standard air pressure of 760 mm Hg in the cabin with about 21% oxygen and up to 1% carbon dioxide. The temperature in the cabin is regulated automatically from 15 to 22° C and the relative humidity is 30 to 70%.

The non-mask-type life support system for the pressure suits of these spacecraft is not connected with the cabin LSS. This system (Figure 3.20) provides suit ventilation during flight in the pressurized cabin and also oxygen flow and suit ventilation in an emergency situation.

Throughout flight, the suit is ventilated by air from the cabin by the fan 1. In the case of primary fan failure, the reserve fan 2 is automatically activated.

The centrifugal fans create a head of no less than 180 mm Hg with air flowrate up to 200 liters(s)/min (the fan requires about 40 W).

The air entering the pressure suit is distributed to ventilate the torso, helmet, and extremities and discharges from the suit through the open helmet faceplate.

The emergency pressure suit LSS comes into operation automatically when the cabin pressure falls to 530 ± 30 mm Hg cabin "altitude" about 3 km). At this instant, the electrically-operated start-up valve actuates and ventilating air begins to flow to the pressure suit from the air bottles 4; through the oxygen regulator 9 at the rate of 35 — 40 liters(s)/min. Upon reduction of cabin pressure to 430 ± 30 mm Hg (cabin "altitude" about 4.5 km), automatic oxygen flow from the bottle 5 is initiated and, at the same time, a signal is sent to close the suit helmet. In this case, the oxygen regulator provides flow

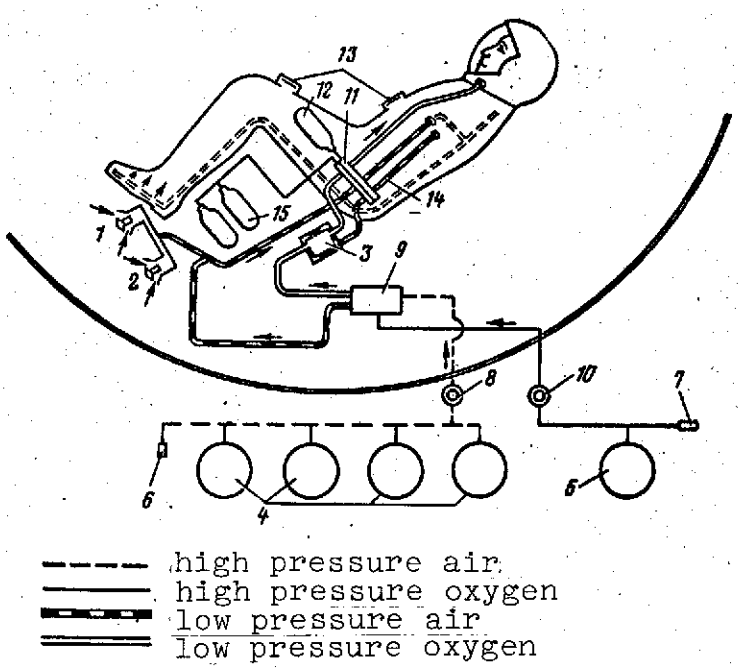


Figure 3.20. Oxygen supply and pressure suit ventilation system in the Vostok spacecraft.

1, 2 — main and reserve fans; 3 — economizer; 4 — compressed air bottle; 5 — oxygen bottle; 6, 7 — fill fittings; 8, 10 — pressure reducers; 9 — oxygen regulator; 11 — single point disconnect; 12 — parachute oxygen bottle; 13 — pressure regulator; 14 — equalizing hose; 15 — oxygen bottle.

of oxygen-air mixture to the pressure suit helmet at a rate of 10.5 — 11.5 liters(s)/min and the volumetric oxygen content in this mixture increases with altitude increase. At the same time, part of the air supplied from the bottles flows directly into the pressure suit ventilation line. At altitudes above 9 km, pure oxygen is directed into the helmet and all the air entering the oxygen regulator (about 40 liters(s)/min) is bypassed to the pressure suit ventilation line.

In the oxygen supply line, there is an economizer 3 — an additional vessel in the form of a rubber bag in a sealed housing. Its purpose is to lower the breathing resistance in the deep inhalation case. /77

During spacecraft descent to the Earth, the cosmonaut is ejected from the cabin, together with the seat, at an altitude of about 7 km. Breathing oxygen in an amount of 25 — 30 liters(s) is supplied to the helmet from two oxygen bottles 15 located on the seat, each containing two liters of oxygen at 200 kG/cm^2 pressure.

The cosmonaut later separates from the seat and descends by parachute. At this time, the breathing oxygen comes from the parachute oxygen bottle 12 with capacity of one liter at 200 kG/cm^2 pressure.

REFERENCES

1. Alekseyev, S. M., et al. Sovremennyye sredstva avariynogo pokidaniya samoletov (Modern Airplane Emergency Escape Systems), Oborongiz, Moscow, 1961.

2. Voronin, G. I. and A. I. Polivoda. Zhizneobespecheniye ekipazhey kosmicheskikh korabley (Life Support for Spacecraft Crews), Mashinostroyeniye, Moscow, 1967.

3. Woodson, W. E. and D. W. Conover. Human Engineering Guide for Equipment Designers (Russian translation), Mir, Moscow, 1968.

4. "The First Spacewalk," Aviatsiya i kosmonavtika, No. 3, 1970.

CHAPTER 4
AUTONOMOUS LIFE SUPPORT SYSTEMS FOR SPACE SUITS

1. Purpose and Requirements

The pressure suit forms a shell around the cosmonaut which protects him against the action of outer space factors while the autonomous life support system (ALSS) creates the microclimate required inside the suit for man's functioning: pressure, gas composition, humidity, and so on. /78

The ALSS is designed to ensure cosmonaut functioning under the following conditions:

(a) when performing scientific studies and making measurements in open space;

(b) when repairing the spacecraft or installing equipment on the craft, performing assembly or various other operations;

(c) when performing scientific experiments after landing on the surface of the Moon and planets.

The ALSS can also be used by the cosmonaut when the spacecraft encounters an emergency situation (failure of the onboard LSS, cabin depressurization, and so on).

By analogy with pressurized cabins, on the basis of operating principle, the ALSS can be subdivided into *ventilated* and *regenerative* (open and closed) types. In the ventilated systems, the gas leaving the pressure suit is not purified of the

respiration products and is discharged overboard. In the regenerative systems, the respiration products are absorbed and the oxygen is again used for breathing.

On the basis of constructional characteristics, the ALSS can be subdivided into systems with sealed and nonsealed housing (pack), with evaporative and sublimative cooling, and with one or two loops.

Soviet and foreign experience in using ALSS on various flight vehicle types makes it possible to present the following considerations which can be used in developing such systems [25].

1. The oxygen partial pressure should be no less than 197 mm Hg and no more than 420 mm Hg.

2. The permissible carbon dioxide partial pressure in the helmet depends to a considerable degree on suit use duration and can be determined from the data shown in Figure 2.4.

3. The relative humidity in the helmet should be maintained in the range 40 — 60%.

4. The temperature of the air entering the suit will vary as a function of the ambient medium properties and the cosmonaut physical workload in the range from 10 to 80° C.

5. To create normal helmet ventilation conditions, the /79
oxygen flow to the helmet of the non-mask type pressure suit should be approximately 40 — 50 liters/min (in order to remove the exhaled carbon dioxide and moisture); regulated flow of up to 350 liters/min (to evaporate perspiration and create the required temperature regime) is necessary for ventilating the space inside the suit.

TABLE 4.1

MAXIMUM PERMISSIBLE CONTAMINANT CONTENT IN THE ATMOSPHERE OF PRESSURIZED AIRPLANE CABINS AND PRESSURE SUITS

Chemical compound	For aircraft pressurized cabins mg/m³	For pressure suits mg/m³	For work areas in mg/m³	
			USSR*	USA****
Ammonia	—	5**	20	70
Carbon monoxide	20**	10 — 20	20	110
Hydrogen sulfide	—	30	10	—
Oxides of nitrogen	5.0	5	5.0	9
Fuel vapors (gasoline, kerosene)	300	—	300	—
Carbon dioxide	36,000***	see data of Figure 2.4	1,860	—
Ozone	—	—	0.1	0.2
Acetone	—	—	200	—
Phenol	—	5	5	—
Methyl alcohol	—	—	50	—
Hydrocarbons	—	200	300	—

*SN-245 — 63 (for 8 hours 6 times a week).

**Odor sensation threshold [1].

***Limit partial pressure 15 mm Hg [8].

****Man Under Water and In Space, collection edited by O. G. Gazenko and A. M. Genina, Voyenizdat, Moscow, 1967.

6. The data shown in Table 4.1 can be used to design the filters to remove the harmful vital activity products from the air supplied to the pressure suit.

7. It is desirable that units whose noise level is above 80 dB in the frequency range up to 4000 Hg not be used in the life support system. Brief increase of the overall noise level to 90 dB can be permitted in exceptional cases.

8. The heat exchangers should be designed to remove 450 — 600 kcal/h of heat released per individual.

9. In pressure suit calculations, we should use:

— a design "altitude" of 7 km (308 mm Hg), at which the possibility of altitude sickness occurrence is eliminated;

— a working "altitude" of no more than 10 km (197 mm Hg), at which ground-level breathing conditions ($p_{O_2 alv}$ = 110 mm Hg) are ensured.

10. It is necessary that the system:

— operate properly in all cosmonaut positions at the specified temperatures and pressures;

— have high survivability in emergency situations and operational reliability; /80

— be fire and explosion proof during servicing and in operation;

— be constantly ready for operation.

11. Very important system characteristics are long operating life, repairability, least possible weight and size.

12. The following conditions must be considered in the system:

— all cosmonaut equipment must be donned and doffed by the cosmonaut himself without any outside help and in the shortest possible time;

— monitoring and control equipment should be located so that they can be viewed directly by the cosmonaut;

— provision must be made for the possibility of charging the system with oxygen and water for multiple reuse and also replacement of individual system components;

— automatic operation must be provided for the system components which regulate the gas composition and pressure in the pressure suit;

— provision must be made for the possibility of regulating the temperature of the gas mixture supplied to the suit.

13. High system component operating reliability under the following conditions is mandatory:

— in a pure oxygen medium;

— with variation of the absolute pressure in the pressure suit from 1200 to 100 mm Hg, temperature from 5 to 80° C, and with air humidity up to 98 ± 2%;

— during vibrations and linear accelerations.*

14. The following data can be used in system calculations:

— the long-term energy expenditures of a single cosmonaut when working for 2 — 6 hours amount to no less than 400 — 600 kcal/h;

— the peak energy expenditures in the course of 5 — 10 minutes may reach 1000 kcal/hr;

— the moisture liberation of a single cosmonaut in a liquid cooled garment (LCG) amounts to 100 — 200 g/h, without the LCG the value reaches 200 — 600 g/h.

---

*The magnitude of the accelerations is defined by the technical specifications.

15. The oxygen flowrate supplied to the ALSS is determined by the quantity necessary for breathing, the magnitude of the oxygen leakage through joints as a result of poor sealing, and the amount of oxygen necessary for flushing the system and the pressure suit.

The amount of oxygen expended for breathing depends on the pressure suit type and is approximately:

— for the ventilated mask type pressure suit with W_{pv} = 15 liters(s)/min (see Figure 3.17) under the design conditions ("altitude" 7 km) no less than 5 liters(s)/min; in the working regime ("altitude" 10 km) no less than 4 liters(s)/min;

— for the non-mask pressure suit of the ventilated type (see Figure 3.16) in the design regime ("altitude" 7 km) no less than 16.5 liters(s)/min; for operation in the working regime ("altitude" 10 km) no less than 10.5 liters(s)/min;

— for the non-mask suit of the regenerative type with heat output of 400 kcal/h no less than 80 liters(s)/h (1.36 liters(s)/min).

The oxygen losses resulting from leakage usually do not exceed 0.5 liters(s)/min.

The oxygen consumption for flushing the system and the pressure suit amounts to about 200 liters(s).

The ALSS is a complex engineering system having several subsystems. ALSS weight depends on the construction and the operating time for which it is designed; however, some components have a definite weight regardless of the system operating time (pressure gages, gas analyzers, fans, electric motors, etc.). /81

The components whose weight varies as a function of the operating time include the oxygen bottles, absorption canisters, and so on.

The ALSS of the ventilated type satisfies the needs of the individual in regard to oxygen; however, it does not remove the heat generated by the individual in the case of hard physical work.

The energy capacity of the regenerative ALSS equipped with an evaporative heat exchanger can be characterized by the heat capacity of the coolant supply in the system. For example, with a supply of 3 kG of coolant (water) which evaporates completely in the operating process, the energy capacity of such a system will be $580 \cdot 3 = 1740$ kcal.

2. Ventilated Autonomous Life Support Systems

Ventilated ALSS were used in the first space walk of cosmonaut A. Leonov and during the Gemini program flights in the USA. The use of such systems to support short-term (up to one hour) space walks in the future is possible. The distinctive feature of the ventilated ALSS is their comparative simplicity and reliability.

At the present time, ALSS of the ventilation type with free (continuous flow) or positive (injector) oxygen feed are in use.

A schematic of an ALSS of the first type is shown in Figure 4.1. In this system, the oxygen is contained in bottles under high pressure. As the oxygen flows into the pressure suit, its pressure is reduced to the operating pressure (2 — 4

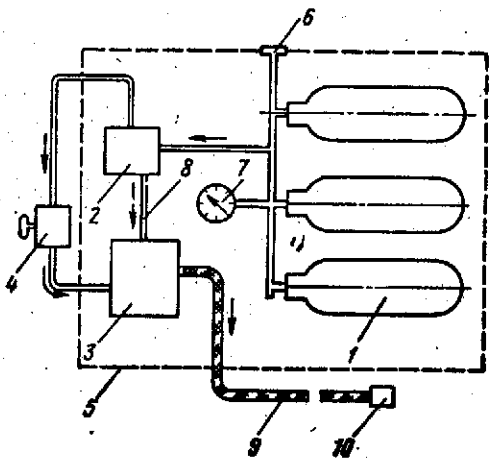


Figure 4.1. Schematic of hypothetical autonomous life support system of the ventilation type with continuous oxygen flow.

1 — oxygen bottle; 2 — pressure reducer; 3 — flow regulator; 4 — remote control; 5 — pack housing; 6 — filler; 7 — pressure gage; 8 — emergency oxygen flow line; 9 — oxygen hose to pressure suit; 10 — disconnect.

kG/cm^2) in the two-stage pressure reducer 2, which is at the same time the on-off controller.

Oxygen flow to the pressure suit is accomplished with the aid of the remote control unit 4 and the regulator 3, with the flowrate being regulated automatically as a function of the pressure in the pressure suit. For example, on the Earth, the oxygen flowrate will be no less than 25 — 35 liters(s)/min, with an "altitude" in the suit of 7 km, the rate will be no less than 20 liters(s)/min, and with an "altitude" in the suit above 10 km, the rate will be no less than 12 — 15 liters(s)/min. If the oxygen pressure in the pressure suit drops below the permissible level (0.23 — 0.25 kG/cm^2), emergency oxygen flow (25 — 30 liters(s)/min) through the line 8 is activated automatically or manually.

The entire system can be installed in a backpack.

System operation with oxygen flowrate 15 liters(s)/min for 180 minutes is possible. /82

Typical weight characteristics of such a system are shown in Table 4.2.

TABLE 4.2

TYPICAL WEIGHT CHARACTERISTICS OF BACKPACK ALSS OF THE VENTILATION TYPE FROM LITERATURE DATA

Name of assemblies, parts, and components (locations shown in Figure 4.1)	Weight, kG
O_2 bottles 1 (3 each)*	9.0
Components	7.74
reducer 2	
O_2 flow regulator 3	
remote controller 4	
pack housing 5	
fill fitting 6 with tee	
pressure gage 7	
emergency O_2 line 8	
flex hose 9 and disconnect 10	
O_2 supply (about 2700 liters(s))	3.86
Total	20.6 kG

*Capacity of each bottle 2 liters, pressure about 500 kG/cm^2.

Let us determine the weight of the components and consumables required for operation of this system for an hour. The weight of the bottles for storing 1.72 kG of O_2 with weight 2.3 kG per kG O_2 is 4.0 kG. Thus, the overall weight of the components and consumables for system operation for an hour will be 1.72 + 4.0 = 4.56 kG.

Another variant of the ventilated ALSS in which the major portion of the oxygen supply is located on-board the spacecraft rather than in a pack is shown in Figure 4.2.

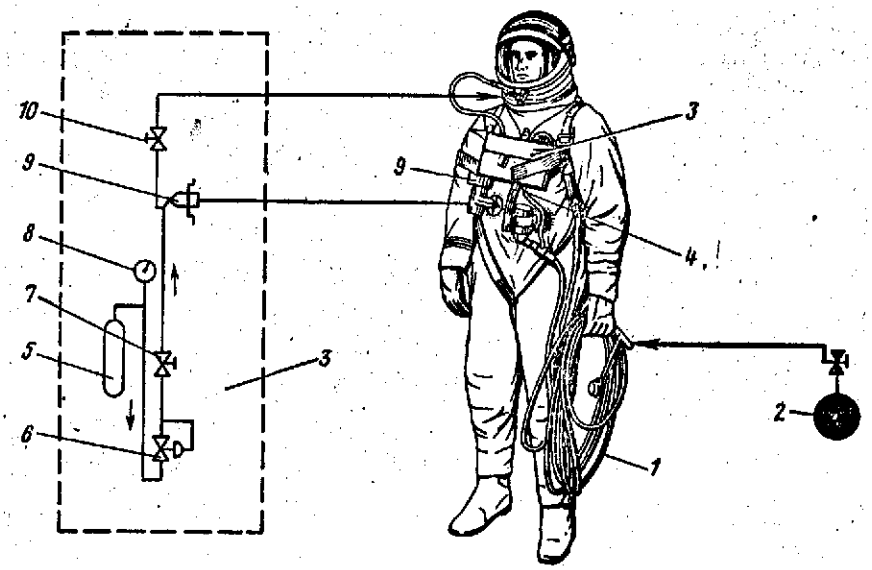


Figure 4.2. Schematic and general view of American G-4C, ventilated pressure suit ALSS.

1 — tether connecting astronaut with vehicle in open space; 2 — ship's liquid oxygen gasifier; 3 — pack with emergency life support system units; 4 — telemetry monitor line disconnect; 5 — emergency oxygen supply bottle; 6 — pressure reducer; 7 — shutoff valve; 8 — pressure gage; 9 — oxygen flow regulator; 10 — emergency oxygen flow actuation valve.

In this system, there is a bottle 5 with an emergency oxygen supply, pressure reducer 6, shutoff valve 7, and oxygen flow regulator 9. The oxygen is fed from aboard the ship to the system through a flexible hose — the tether 1.

A schematic and general view of a *ventilated ALSS with positive oxygen delivery by an ejector* is shown in Figure 4.3.

In this system, the injector 10 can operate in normal and high oxygen flowrate regimes, regulated by the position of the valve 11. The oxygen, respiration products, and water vapor leaving the suit are partly discharged into surrounding space through the pressure regulator 9 and are partly directed to the

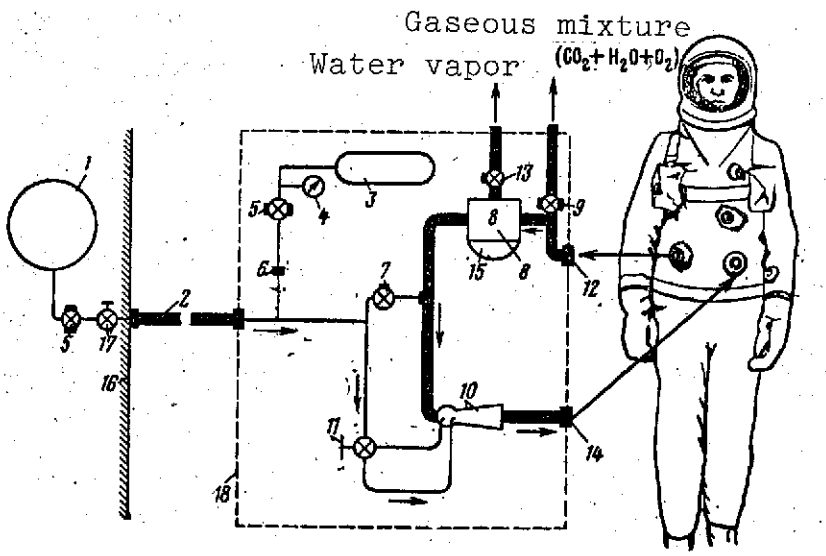


Figure 4.3. Schematic and general view of autonomous life support system with forced oxygen feed by injector.

1 — ship's oxygen bottle; 2 — oxygen hose; 3 — emergency oxygen supply bottles; 4 — pressure gage; 5 — pressure reducers; 6 — orifice; 7 — emergency oxygen flow regulator; 8 — evaporative heat exchanger; 9 — system pressure regulator; 10 — injector; 11 — two-position valve; 12, 14 — hose disconnects; 13 — heat exchanger valve (pressure regulator); 15 — coolant (water) vessel; 16 — ship's skin; 17 — shutoff valve; 18 — pack contour.

heat exchanger 8 for cooling, after which they are drawn in by the injector 10 and again enter the pressure suit. Thanks to this gas circulation, the heat generated by man is removed from the suit.

If the pressure in the suit falls below the specified value, the regulator 7 initiates additional oxygen flow. The bottle 3 /84 with the emergency oxygen supply is connected to the pressure suit manually with the aid of a valve.

The flexible hose 2, 6 — 9 meters long, through which the oxygen is supplied, connects the cosmonaut with the spacecraft in open space. In the evaporative heat exchanger 8, the coolant used is water and the water supply is stored in the tank 15. The operation of the evaporative heat exchanger is controlled by the valve 13, which is adjusted to a pressure at which the water in the heat exchanger boils and evaporates at a temperature of about 10° C.

An oxygen flowrate of 15 liters(s)/min is required in order to supply 150 liters(s)/min (1.28 kG/h) of oxygen to the suit with an injection coefficient of 10.

The weight of the gasifier for storing liquid oxygen in the amount necessary for an individual to stay in open space for an hour amounts to about 2 kG (1.5 kG/kG O_2).

The energy capacity of this system in terms of heat is determined by the amount of moisture (perspiration) which the oxygen supplied for suit ventilation can carry away (evaporate).

The air leaving the suit at a temperature of 24° C and 80% saturation contains 17.5 kG/m^3 of moisture in vapor form.

Upon cooling of the air in the heat exchanger to 10° C, part of the moisture condenses (8.1 g/m^3). When the air flowrate is 150 l (s) min, 1.21 g/min moisture (73 g/hr) will be held back. Condensation of the vapor in the heat exchanger leads to the release of about 43 kcal of heat. With account for the heat 28 kcal/h expended in cooling the air (from 24 to 10° C), the overall heat removal amounts to 61 kcal/h. With heat output of 200 kcal/h and permissible heat accumulation of 100 kcal, the system operating time is 39 minutes.

In order to condense the vapor (73 g/h) in the heat exchanger, it is necessary to expend about 125 g/h of coolant (water). In this case, the hourly oxygen and water flow amounts to 1.405 kG. With account for gasifier weight (2 kG), we have a weight of 3.4 kG.

This weight is less by a factor of 1.7 than the weight of the ventilated system with unrestricted oxygen flow.

An example of such an ALSS is that fabricated in the USA for flights in the Gemini program and located on the astronaut's chest, as shown in Figures 6.11 and 6.12.

3. Regenerative Autonomous Life Support Systems

The ALSS of the regenerative type operate with closed cycle, since the gaseous mixture leaving the suit and consisting of oxygen, respiration products, and moisture vapor is purified and reused in the breathing and ventilation system.

At the present time, we can note the following constructional variants of such ALSS:

— with non-regenerable absorbers;

— with regenerable absorbers;

— with two-phase atmosphere.

A schematic of an ALSS with nonregenerable absorber is shown in Figure 4.4. The gas mixture leaving the suit is purified of the solid particles suspended in the mixture in the filter 1.

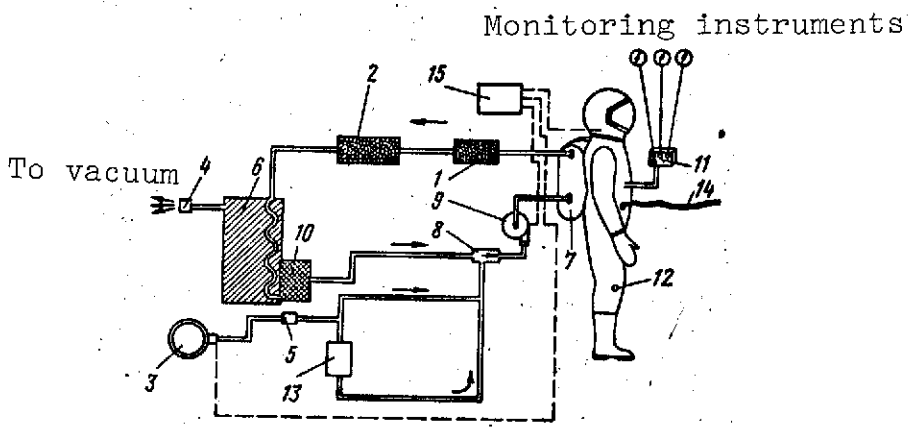


Figure 4.4. Schematic of autonomous life support system with nonregenerable absorber.

1 — filter to remove solid particles suspended in gaseous mixture; 2 — regeneration canister (carbon dioxide, carbon monoxide, and dust absorber); 3 — oxygen bottle; 4 — discharge valve; 5 — pressure reducer; 6 — heat exchanger; 7 — pack; 8 — mixer; 9 — centrifugal fan; 10 — moisture collector; 11 — system control panel; 12 — suit pressure regulator; 13 — flow controller; 14 — tether; 15 — telemetry monitor unit.

Absorption (sorption) of the carbon dioxide, carbon monoxide, and dust present in this mixture takes place in the canister 2 with nonregenerable (non-restorable) absorber. In the heat exchanger 6, the oxygen is cooled to the required temperature and again flows to the pressure suit.

The oxygen is stored under high pressure in the bottle 3. /85
The reducer 5 lowers the oxygen pressure to 3 — 5 kG/cm^2.

The control panel 11 has monitoring instruments which permit following the operation of the life support system.

The fan 9 is driven by an electric motor which is fed from the spacecraft electrical system.

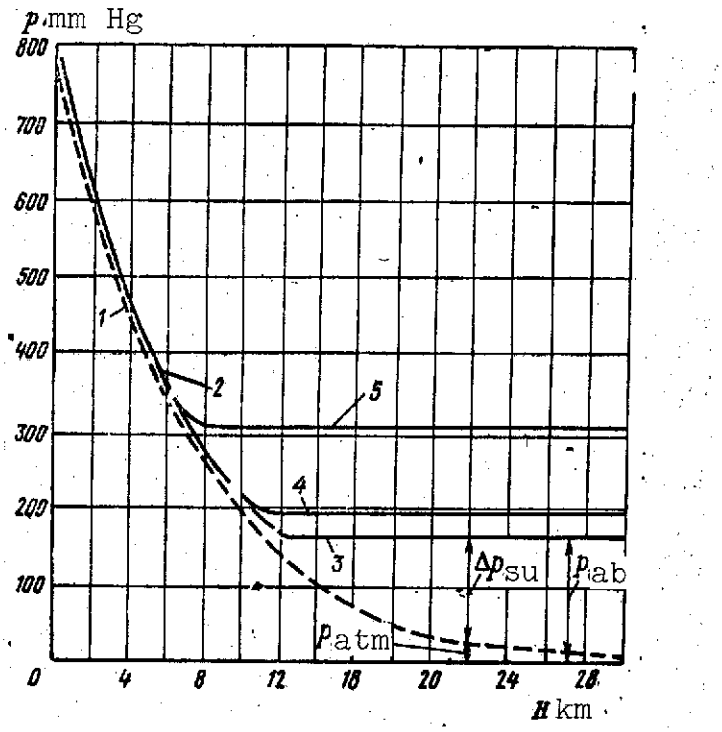


Figure 4.5. Suit pressure variation with altitude H.

1 — atmospheric pressure variation in standard atmosphere; 2 — with 0.02 — 0.04 kG/cm^2 differential pressure created by ventilating air; 3 — maximum "altitude" in suit (147 mm Hg) for flight up to 15 minutes; 4 — working "altitude" in suit (197 mm Hg) which provides ground level breathing conditions; 5 — design "altitude" (308 mm Hg) in suit based on eliminating possibility of altitude sickness occurring.

The pressure in the "suit pack" system is maintained automatically at a definite level by the regulator 12 on the suit. Regulation of the pressure as a function of altitude is accomplished in accordance with the curve in Figure 4.5.

Upon reduction of the pressure in the suit (as a consequence of leakage in the suit or the life support system), secondary (emergency) oxygen flow is activated by the flow controller 13 (see Figure 4.4).

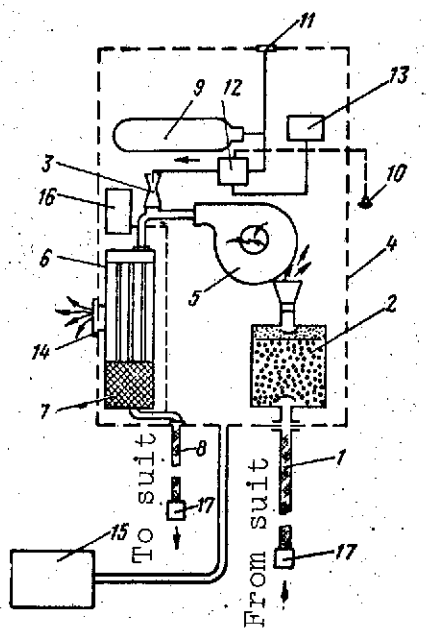


Figure 4.6. Schematic of hypothetical autonomous portable pressure suit life support system with nonregenerable absorber and hermetic pack.

1, 8 — flexible hoses; 2 — canister with nonregenerable absorber; 3 — injector; 4 — hermetic pack; 5 — fan; 6 — heat exchanger; 7 — moisture collector; 9 — oxygen bottle; 10 — oxygen flow remote control handle; 11 — filler; 12 — feed module; 13 — flow controller; 14 — heat exchanger valve; 15 — system control panel; 16 — telemetry monitoring system instrumentation assembly; 17 — disconnects.

In the subject ALSS, all the components are sealed, while the backpack is not sealed and serves only to store the components and protect them against mechanical damage.

Typical weight data for the system are shown in Table 4.3.

A schematic of an autonomous portable life support system with nonregenerable absorber (sorbent) and hermetic pack is shown in Figure 4.6.

In this system, the oxygen which has been purified in the regenerative canister 2 enters the hermetic pack 4. The centrifugal fan 5 draws the oxygen from the pack and directs it to the evaporative heat exchanger 6. In the moisture collector 7, the vapor present in the oxygen is condensed into droplets and retained.

The feed module 12 is a two-stage pressure reducer in the first stage of which there is an on-off selector which permits starting and stopping the oxygen /87 flow by means of the remote control 10. The pressure is reduced to 10 — 15 kG/cm^2 in the first stage and 3 — 5 kG/cm^2 in the second stage.

TABLE 4.3

TYPICAL WEIGHT CHARACTERISTICS OF PORTABLE REGENERATIVE ALSS WITH NONREGENERABLE ABSORBER

Name of assemblies, parts, and components (locations shown in Figure 4.4)	Wt. kG	Remarks
O_2 bottle 3, capacity 1 liter with differential pressure about 500 kG/cm^2	1.2	for 3-hr stay in open space
Components:	20.2	
filter 1		
regenerator canister 2		for absorbing 150 liters of CO_2
heat exchanger 6		for absorbing 1200 kcal of heat
mixer 8		
centrifugal fan 9		
fan heater		
moisture collector 10		
control panel 11		
instrumentation		
remote control 11		
pack with straps 7		
lines and fittings		
O_2 supply, 400 liters(s)	0.6	
Coolant (water)	3.0	
Total	25.0 kG	

The computed weight of the feed module does not exceed 1.3 kG, the filler 11 with check valve for filling the bottle 9 with gaseous oxygen weighs 0.3 g.

Electric current for the fan and instrumentation comes from the ship's electrical sources. Operation of the system is monitored by instruments mounted on the control panel 15.*

*Abramov, I. P. "Some Results of ALSS Operation During Soyuz-4 and Soyuz-5 Flights," Kosmicheskaya biologiya i meditsina, No. 4, 1970.

The injector 3 is activated in case of fan failure automatically or manually by means of the remote control.

The instrument complex, mounted in the assembly 16, includes instruments for measuring:

— carbon dioxide content and oxygen partial pressure in the suit helmet;

— temperatures of the oxygen (at pressure suit inlet and outlet), coolant, and suit surface at several points;

— pressure in the suit; /88

— oxygen quantity (oxygen pressure in the bottle).

The design weight of the instrumentation is on the order of 0.3 — 0.4 kG.

In case of ALSS possible malfunctions, a warning system is activated and backup systems in the pack are activated. Specifically, in case of pressure decrease in the suit, emergency oxygen flow is automatically activated.

Control of the pack system is accomplished by special levers mounted at convenient locations. The pressure suit system also includes equipment for medical monitoring of the cosmonaut's condition and monitoring the operation of the individual system components.

The ALSS pack must be light and convenient, its construction must permit rapid doffing and donning of the pack without outside help. The most essential elements of the pack construction are the housing and the harness straps.

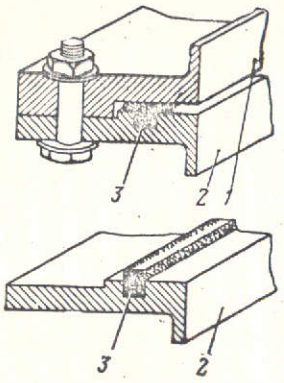


Figure 4.7. Design variant of device for sealing pressure suit autonomous life support system pack cover.

1 — pack cover; 2 — pack housing; 3 — rubber seal.

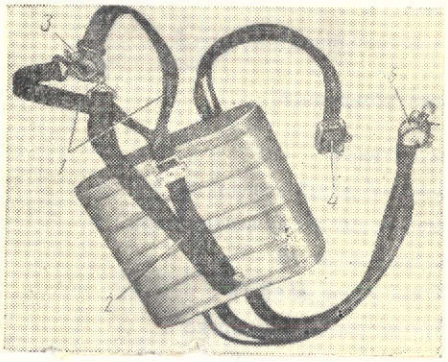


Figure 4.8. Pressure suit autonomous life support system harness straps.

1 — shoulder straps; 2 — lower strap; 3 — lock; 4 — ALSS remote controller; 5 — single point disconnect.

One possible version of the arrangement for sealing the pack cover is shown in Figure 4.7, and the harness system is shown in Figure 4.8.

We take the following as the basic data for system design: breathing oxygen flowrate 80 liters(s)/h and leakage compensation flowrate 30 liters(s)/h. CO_2 evolution for respiration coefficient 0.8 amounts to 64 liters(s)/h.

The weight of the consumables with account for the weight of the units necessary for their storage for operation of this system for one hour is:

Oxygen	0.154 kG
Absorber	0.3 "
O_2 bottles	0.354 "
Coolant (water) for removing heat (130 kcal/h)	0.26 "
Total	1.068 kG

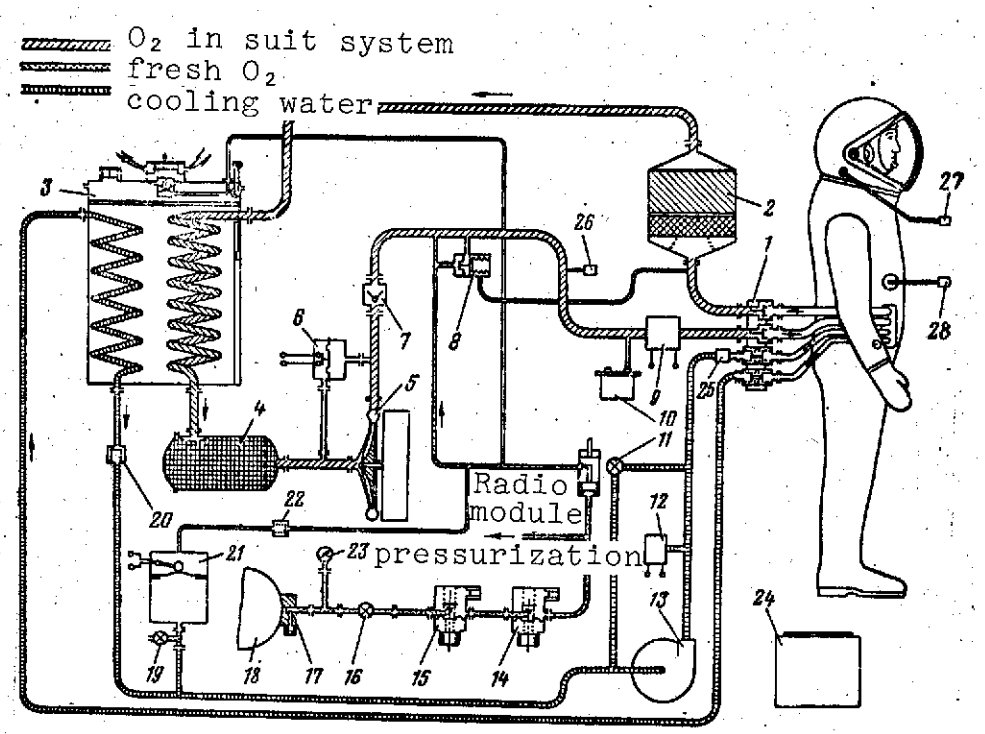


Figure 4.9. Hypothetical ALSS with nonregenerable absorber and additional loop for cooling the water circulating in the cosmonaut's liquid cooled garment.

1 — single point line disconnect; 2 — regeneration canister with nonregenerable absorber; 3 — heat exchanger; 4 — moisture absorber; 5 — fan; 6 — operating fan sensor; 7 — check valve; 8 — O_2 leakage compensator; 9 — CO_2 gas analyzer; 10 — O_2 pressure sensor; 11 — valve; 12 — H_2O pressure sensor; 13 — water pump; 14 — stage II pressure reducer; 15 — stage I pressure reducer; 16 — valve; 17 — filler; 18 — oxygen bottle; 19 — water valve; 20 — check valve; 21 — water tank; 22 — check valve; 23 — pressure gage; 24 — electric battery; 25 — H_2O temperature sensor; 26 — humidity sensor; 27 — radio communication lead; 28 — telemetry lead.

A schematic of an ALSS with nonregenerable absorbers and a secondary loop for cooling the water circulating in the cosmonaut's liquid cooled garment (LCG) is shown in Figure 4.9. In /89 this system, the gaseous mixture with oxygen leaving the suit is purified of the respiration products present in the mixture in the canister 2.

The purified oxygen is then cooled in one loop of the evaporative heat exchanger 3 and directed to the pressure suit. Oxygen circulation in the system is provided by the fan 5. The other heat exchanger loop, which cools the water circulating in the LCG, consists of the pump 13, water tank 21, valve 11, and check valve 20.

The temperature of the water in this loop is regulated by means of a bypass line and valve 11 (the principle and operating characteristics of the liquid cooled garment are examined in Chapter 7). The oxygen supply is stored in the bottle 18. The oxygen pressure is lowered by the pressure reducers 14 and 15.

The approximate weight characteristics of this system are shown in Table 4.4.

The weight of the components and consumables required for operation of the ALSS with nonregenerable absorbers and secondary loop for cooling the LCG water for one hour is: /90

Oxygen	0.154 kG
O_2 bottles	0.354 "
Coolant (water) for gas circulating in system	0.072 "
Coolant (water) for liquid circulating in liquid cooled garment (350 kcal/h)	0.6 "
Absorber canister	0.7 "
Total	1.88 kG

The operational duration of the LSS examined above will be determined by the operating time of the nonregenerable canisters which absorb the carbon dioxide and moisture released by the individual during breathing. If this time is less than the

TABLE 4.4

APPROXIMATE WEIGHT BREAKDOWN OF PORTABLE REGENERATIVE ALSS WITH LCG COOLING LOOP

Name of units, assemblies, parts, and components (locations shown in Figure 4.9)	Weight kG
Oxygen unit	5.6
O_2 bottle 18 capacity 1 liter with diff. pressure about 500 kG/cm^2	
Valve 16 with fill fitting	
Stage I reducer 15	
Stage II reducer 14	
Lines and fittings	
Other components	
Regeneration system	9.2
Absorber canister 2	
Fan with motor 5	
Heat exchanger 3	
Pump 13 with motor	
Water tank 21	
Lines and fittings	
Other components	
Other equipment	8.9
Expendables	5.6
Total	
ALSS without consumable	23.7
ALSS fully charged	29.3

required duration of continuous pressure suit usage, the exhausted absorbers must naturally be replaced, which in practice is possible only after turning the system off and temporarily terminating use of the pressure suit. The sorbent operating time can be increased by regeneration (desorption).

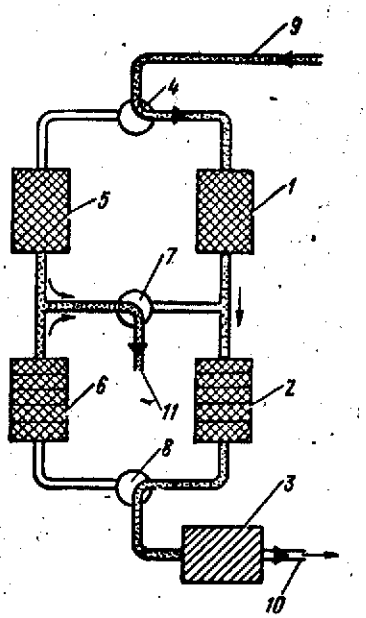


Figure 4.10. Hypothetical ALSS with regenerable absorbers.

1, 5 — regenerable moisture absorbers; 2, 6 — regenerable CO_2 absorbers; 3 — absorber for CO and other contaminants; 4, 7, 8 — three-way valves; 9 — hose for gas mixture discharge from suit; 10 — hose for purified oxygen flow to suit; 11 — gas discharge into space.

A schematic of an ALSS with regenerable absorbers is shown in Figure 4.10. The gaseous mixture leaving the suit and containing carbon dioxide, moisture, and contaminants is dried as it flows through canister 1, and in canister 2 carbon dioxide is removed. Absorption of the remaining contaminants (carbon monoxide and odors) takes place in canister 3. By use of valve 4, the gaseous mixture can be directed to canisters 1 and 2 or to canisters 5 and 6. The valve 7 permits venting the group of canisters to outer space for recovery (desorption) of the absorber and the valve 4 permits connecting the pressure suit to one group of canisters or the other. When connected to valve 7, the moisture accumulated in canisters 1 and 5 evaporates, freezes, and sublimates. As a result, the canisters are cooled and therefore, heat must be expended to warm them for reuse. When canister 2 is connected to space the carbon dioxide accumulated in the canister absorber exhausts into space. /91

Otherwise, this system with regenerable absorbers does not differ from the ALSS shown in Figure 4.9.

It is believed that the systems with regenerable absorbers will find application for long-term (more than 10 — 15 hours) cosmonaut stay in open space.

The weights of the components, containers, and consumables for operation of the ALSS with regenerable absorbers for one hour is

Oxygen	0.154 kG
O_2 bottles	0.354 "
Coolant (water) for gas and liquid circulating in system (heat output 400 kcal/h)	0.67 "
Total	1.178 kG

The pressure suit life support system with a two-gas atmosphere is based on using oxygen and helium in the system. In this system with 300 mm Hg total pressure in the suit, the oxygen partial pressure is no less than 160 mm Hg. At these pressures, the two gases can be premixed and stored in a single bottle.

With account for possible leakage, it is advisable to increase the oxygen partial pressure, for example — to 200 mm Hg.

In comparison with oxygen and air, helium has significantly higher specific heat at constant volume and thermal conductivity, namely:

	Oxygen	Helium
Specific heat in kcal/kG/°C		
at 0° C	0.218	1.243
at 100° C	0.223	1.243
Thermal conductivity in kcal/m/h/°C		
at 0° C	0.021	0.123
at 100° C	0.028	0.154

/92

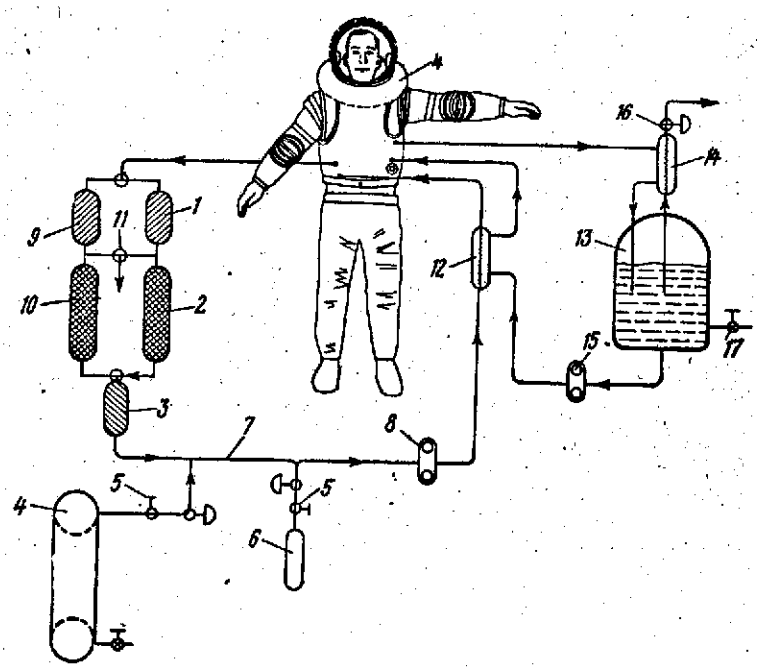


Figure 4.11. Schematic of ALSS with regenerable absorbers and two-gas atmosphere for water-cooled pressure suit.

1, 9 — moisture absorbers; 2, 10 — CO_2 absorbers; 3 — absorber for CO and other gaseous contaminants; 4 — toroidal oxygen bottle; 5 — pressure reducer; 6 — helium bottle; 7 — tubing; 8 — fan; 11 — vacuum valve; 12 — heat exchanger; 13 — water tank; 14 — evaporative heat exchanger; 15 — water pump; 16 — vacuum valve; 17 — filler valve.

These properties of helium make it possible to increase markedly the amount of heat removed by the helium and, consequently, reduce the amount of gas circulating in the system and the fan motor power. The use of helium reduces the fire hazard considerably in comparison with the system using oxygen.

Figure 4.11 shows a schematic of an ALSS with oxygen-helium atmosphere.

The water vapor is absorbed from the gaseous mixture in canister 1, the carbon dioxide is moved in canister 2, and the carbon monoxide, aromatics, and other gaseous substances are

removed in canister 3. The toroidal oxygen bottle 4 is located around the cosmonaut's neck. The gaseous helium is stored in the bottle 6. The canisters 1, 2, 9, 10 can be periodically vented to the ambient medium to restore (regenerate) the absorbers contained therein. /93

Cooling of the gas circulating in the system takes place in the heat exchanger 12.

Cooling of the LCG is accomplished by means of the tank 13 containing the water (coolant) supply, the pump 15 which circulates the liquid, and the evaporative heat exchanger 14. The warm water coming from the LCG flows through the heat exchanger 14 and the cooled water enters the tank 13. The water vapor formed in the evaporator 14 is discharged to space through the valve 16. /94

The arrangement of the components of this system on the astronaut is shown in Figure 4.12.*

Comparative characteristics of the desired LSS are summarized in Table 4.5.

4. LSS Components and Fittings

Lines, Fittings, and Flexible Hoses

The lines and flexible hoses, as well as their connecting fittings are very important elements of life support systems.

The ALSS use both seamless tubing made from stainless steel, copper, and aluminum alloys and welded tubing made from soft aluminum-base alloys.

*Information on the system was presented at the 17th Astronomic Congress in Belgrade (1967) by members of the American delegation.

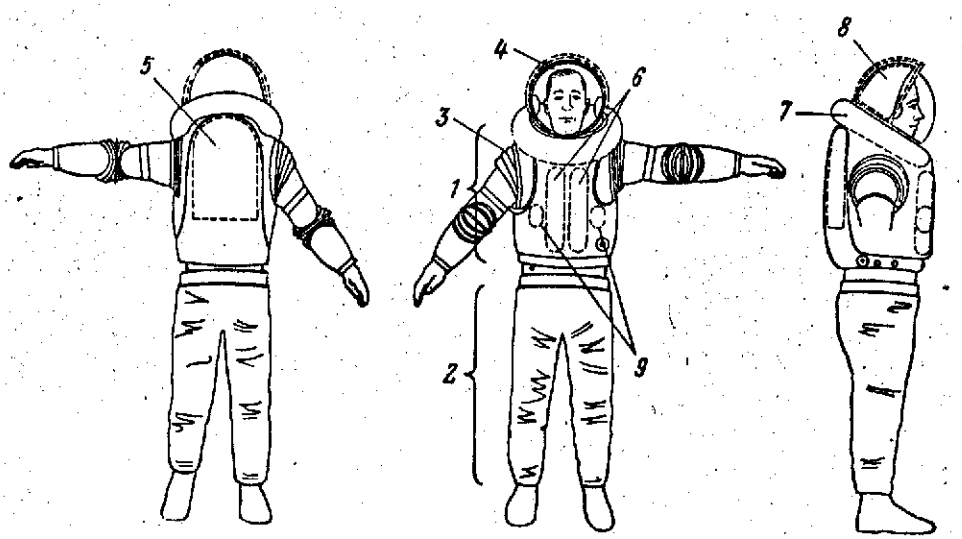


Figure 4.12. American semi-hard pressure suit with ALSS shown in Figure 4.11.

1 — pressure suit hard jacket; 2 — soft part of suit; 3 — shoulder joint; 4 — bubble helmet; 5 — water tank; 6 — CO_2 absorber; 7 — toroidal oxygen bottle; 8 — light filter; 9 — moisture absorber.

Copper tubing (GOST 617 — 64) with wall thickness up to 0.5 mm is used to transport oxygen (air) at high pressures.

Aluminum and aluminum alloy (GOST 4773 — 65) tubing, annealed, tempered, and work-hardened, is also used to transport oxygen (air) and various liquids at low pressures.

Typical permanent tubing connections joined by brazing and welding are shown in Figure 4.13. Welding is accomplished in an argon atmosphere.

In separable tubing connections, wide use is made of tube end flaring as shown in Figure 4.14. When using flares, a surface finish of quality ∇7 must be provided on the flared part of the tubing.

TABLE 4.5

COMPARATIVE CHARACTERISTICS OF VARIOUS ALSS FOR SPACE SUITS

ALSS name	Heat removed kcal/h	Weight of consumables used per hour and their storage assemblies kG	Weight referred to hourly heat removal g/kcal	ALSS application
Ventilation type with continuous oxygen flow (see Figure 4.1)	20—40	6.0	300—150	For short-term (up to 30 minutes) stay in open space
Ventilation type with positive injector oxygen flow (see Figure 4.3)	~ 60	3.4	68—48	For short-term (up to 60 minutes) stay in open space
Regenerative type with nonregenerable absorbers (see Figure 4.4)	150—200	1.6	10.6—8	For comparatively low energy expenditures
Regenerative type (two-loop) with nonregenerable absorbers (see Figure 4.9)	400—500	1.88	4.7—3.7	For high energy expenditures
Regenerative type with regenerable absorbers (see Figures 4.10 and 4.11)	400—500	1.78	2.9—2.3	For extended stay in open space (more than 10 to 15 hours)

Connections with flaring of the tubing are simple in construction and fabrication. It is considered that they are suitable only for pressures up to 200 — 300 kd kG/cm^2. It should be kept in mind that the tubes must be flared in the

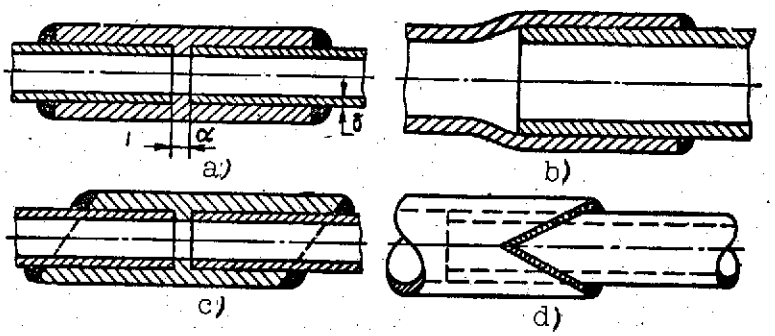


Figure 4.13. Permanent connections sealed by brazing or welding.

a — with straight sleeve ($\alpha \approx \delta$); b — with expansion of one of the tubes; c — with oblique sleeve; d — telescopic.

cold condition, and in this procedure, the formation of cracks in the tube ends and increase of the tube diameter by more than 35% are not allowed.

In the nipple-type tube connections, sealing is provided by good contact of the nipple (spherical or conical) and fitting surfaces (Figure 4.15). Designs with spherical nipples are used to pressures of 300 — 400 kG/cm^2. /95

The spherical nipple is butt welded to the tube (Figure 4.15a) or the tube end is inserted into a recess in the nipple (Figure 4.15b). In the latter case, the fatigue strength of the connection is approximately twice that of the first case. It is recommended that welding be accomplished using high-frequency current.

The flexible hoses for oxygen systems fabricated in the USSR are constructed in the variants shown in Figure 4.16.

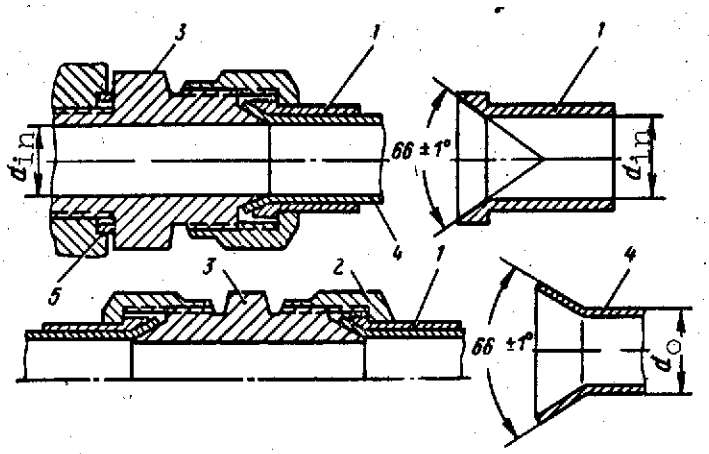


Figure 4.14. Typical ALSS tubing disconnects with sealing along outer cone and flaring of tube ends.

1 — nipple; 2 — nut; 3 — fitting; 4 — flared portion of tube; 5 — sealing gasket (washer).

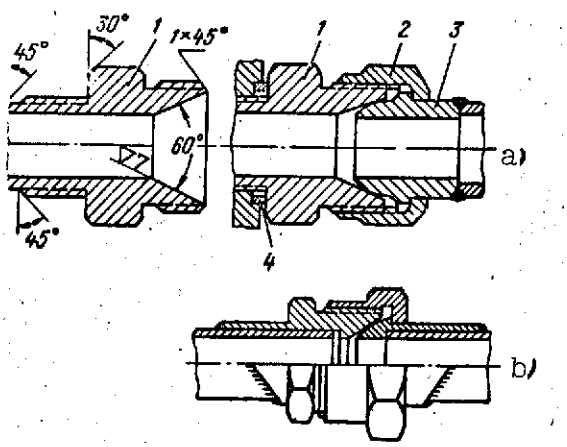


Figure 4.15. Tubing joints sealed along inner cone.

a — spherical nipple butt welded to tubing; b — spherical nipple with tube end inserted into recess; 1 — fitting; 2 — sliding nut; 3 — nipple; 4 — sealing washer.

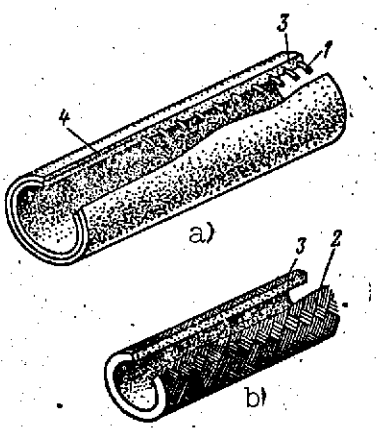


Figure 4.16. Flexible rubber hoses for oxygen breathing equipment fabricated in the USSR.

a — with metal carcass; b — with metal braid; 1 — metal carcass; 2 — metal braid; 3 — rubber layer; 4 — fabric interlayer.

Variant "a" has an inner rubber chamber with one or more layers of fabric at the ends (to reinforce the sleeves), a steel wire spiral, and a rubber outer layer.

In all the variants there are soft sleeves at the hose ends.

These hoses are used at temperatures from -50 to +55° C and working pressure (depending on hose type and diameter) from 0.3 to 8 kG/cm^2.

Rubber hoses with external metal braid are also used (Figure 4.16b). The flexible hoses are fabricated with diameters from 4 to 25 mm.

One of the most advanced techniques for joining flexible hoses is shown in Figure 4.17. It is used for pressures of 100 — 150 kG/cm^2. At the end of the ferrule 1, there is an internal thread with large pitch. During assembly, the hose 3 is first screwed fully into the ferrule 1, which is then screwed onto the conical fitting 2, thus clamping the hose end tightly.

Aluminum alloys (AMg6, D16, V95, and others) and carbon steels are used for components and assemblies operating in an oxygen medium. For oxygen pressures up to 65 kG/cm^2, the components and assemblies may be made from a copper-base alloy.

Rubbers, paronites, teflon, and fiber may be used as gasket material for sealing.

Hydraulic calculation of pressure suit LSS lines is made to determine: /97

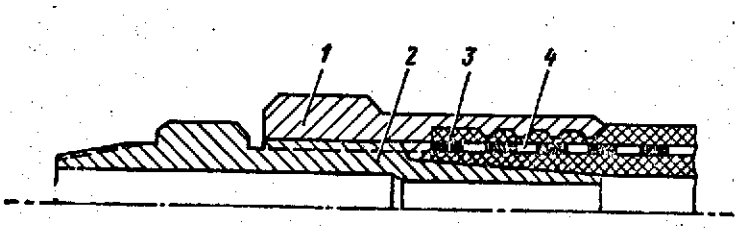


Figure 4.17. Typical connection of rubber fabric hoses.
1 — ferrule; 2 — nipple; 3 — hose; 4 — metal carcass.

— line diameter and hydraulic resistance;

— power required and force characteristics of the energy sources which pump the working fluid through the line.

The basis of line hydraulic calculation is the well-known formula

$$v = Q/F,$$

where v is the specified section average working fluid (water, gas) velocity in the line, F — line section area; Q — specified working fluid flow rate.

The flow of real (viscous) liquids (gases) through the system lines and components is accompanied by head losses in overcoming the resistances, and the magnitude of these losses depends, other conditions being the same, on the nature of the fluid flow.

In the laminar flow case, the head losses due to friction are independent of the roughness on the inner surface of the tube, while for turublent flow this dependence is quite important.

The average height of the individual protuberances determines the magnitude of the absolute roughness k, while the ratio of the latter to the tube inside diameter D determines the magnitude of the relative roughness $\varepsilon = k/D$ (for seamless brass and glass tubing $\varepsilon = 0.0015 — 0.01$, for steel tubing — $\varepsilon = 0.02 — 0.10$.

As is well known, transition from laminar to turbulent flow occurs under definite conditions, characterized by the Reynolds number (criterion) Re.

In application to fluid flow in tubes of circular section [5]:

$$\mathrm{Re} = \frac{vD}{\nu} = \frac{1{,}274Q}{D\nu}, \qquad (4.1)$$

where v is the section average flow velocity, D — line internal diameter, ν — kinematic viscosity ($\nu = \mu/\rho$).

In the calculations, we must remember that the dynamic viscosity of liquids decreases with temperature increase, while that of gases increases.

The dynamic viscosity of gases and vapors at various temperatures can be determined with accuracy adequate for practical calculations from the Sutherland formula [22]:

$$\mu_t = \mu_0 \frac{1 + \frac{C}{273}}{1 + \frac{C}{273 + t}} \sqrt{\frac{t + 273}{273}}, \qquad (4.2)$$

where μ_0 is the dynamic viscosity of the gas at 0° C; C — constant depending on the nature of the gas.

To simplify the calculations, the values of the dynamic viscosity of some gases at various temperatures and the values of the constant C found using (4.2) are presented in Table 4.6, and the kinematic viscosity for the same gases at various temperatures are presented in Table 4.7.

Calculations have shown that the pressure influence on gas viscosity can be neglected in determining the dynamic viscosity μ at pressures up to 10 kG/cm^2.

The kinematic viscosity of a mixture of gases is determined from the Mann approximate formula [2]:

$$\nu_m = \frac{100}{\frac{V_1}{\nu_1} + \frac{V_2}{\nu_2} + \frac{V_3}{\nu_3} + \ldots}, \qquad (4.3)$$

where ν_1, ν_2, ν_3 are the kinematic viscosities of the individual gaseous components of the mixture; V_1, V_2, V_3, ... are the volumetric contents of the gaseous components of the mixture (in percent). /98

The following approximate formula [23] is used to determine the dynamic viscosity of a mixture of gases:

$$\mu_m = \frac{1000}{\frac{G_1}{\mu_1} + \frac{G_2}{\mu_2} + \frac{G_3}{\mu_3} + \ldots}, \qquad (4.4)$$

where μ_1, μ_2, μ_3 are the dynamic viscosities of the gaseous components, G_1, G_2, G_3 are the percent contents of the gaseous components of the mixture by weight.

The values of the dynamic and kinematic viscosities of water for various pressures and temperatures necessary for the calculations are presented in Table 4.8.

TABLE 4.6*

DYNAMIC VISCOSITY OF GASES AT 760 mm Hg PRESSURE AND VARIOUS TEMPERATURES AND VALUES OF THE CONSTANT C IN MICROPIEZES CALCULATED USING THE SUTHERLAND FORMULA [2]

Gas	Gas temperature in ° C							Value of constant C
	—20	0	20	40	60	80	100	
Nitrogen	157,5	166	174,8	183,5	192,5	200	208	104
Hydrogen	80,4	84,0	88,0	91,8	95,9	99,6	103,0	71,0
Water vapor	82	89,3	96,7	104,0	111,3	118,7	126,0	961
Air	162,0	171,2	180,9	190,4	199,8	208,9	219,0	111
Helium	175,0	186,0	195,5	204,0	213,5	220,5	229,0	0
Oxygen	181,0	192,0	202,5	213,0	223,5	234,0	244,0	125
CO_2	128	138,0	147,0	157,0	167,0	175,5	184,5	254

*Commas in the numbers indicate decimal points.

TABLE 4.7*

KINEMATIC VISCOSITY OF GASES IN cSt FOR 760 mm Hg PRESSURE AND VARIOUS TEMPERATURES [2]

Gas	Gas temperature in °C						
	—20	0	20	40	60	80	100
Nitrogen	11,67	13,3	15,0	16,8	18,8	20,6	22,3
Hydrogen	84	93,5	105,0	117,3	130	143	156,6
Water vapor	9,5	11,2	12,9	14,8	16,9	18,6	21,5
Air	11,6	13,2	15,0	16,9	18,8	21	23
Helium	9,1	10,4	11,7	13,1	14,5	16,0	17,5
Oxygen	11,4	13,4	15,3	17,1	19,0	21,1	23,4
CO_2	5,62	7,0	8,0	9,0	10,3	12,1	12,8

*Commas in the numbers indicate decimal points.

For each specific system there is some range of critical Re values for which the gas flow regime in the line changes.

The laminar flow regime in tubes of circular cross section /99
corresponds to values Re $\leq$ 2200 — 2300, and the turbulent regime corresponds to Re $\geq$ 2200 — 2300 [2].

TABLE 4.8*

DYNAMIC μ AND KINEMATIC ν VISCOSITIES OF WATER FOR VARIOUS TEMPERATURES AND PRESSURES [22]

Viscosity	Pressure in kG/cm²								
	1,0					1,03	15,86	87,61	214,68
	Water Temperature in °C								
	0	20	40	60	80	100	200	300	370
$\mu \cdot 10^6$ in kG/m²	182,3	102,4	66,6	47,9	36,2	28,8	13,9	9,3	5,8
$\nu \cdot 10^6$ in m²/s	1,792	1,006	0,659	0,478	0,365	0,295	0,158	0,128	0,126

*Commas in the numbers indicate decimal points.

The head losses during flow of a real (viscous) liquid (gas) through a line are caused by the head losses (h_f) resulting from gas friction on the tube wall and the local head losses (h_l) in segments where the flow velocity changes in magnitude or direction.

The frictional head losses h_f in straight lines are found from the Darcy formula [15]:

$$h_f = \lambda \frac{l}{D} \frac{v^2}{2g}, \tag{4.5}$$

where λ is the friction resistance coefficient, l — line length, D — line internal diameter, v — average velocity, g — acceleration of gravity, or

$$\Delta p = \lambda \gamma \frac{l}{D} \frac{v^2}{2g}, \tag{4.6}$$

where Δp is the head loss in kG/cm².

In calculations using (4.5) and (4.6), we can take, for laminar flow

$$\left.\begin{aligned} \lambda_{lam} &= \frac{64}{Re} = \frac{64\nu}{vD} \text{ for circular pipe [4];} \\ \lambda_{lam} &= 0.89\,\frac{64}{Re} \text{ for rectangular pipe [19];} \\ \lambda_{lam} &= 1.5\,\frac{64}{Re} \text{ for annular gap [19].} \end{aligned}\right\} \quad (4.7)$$

The influence of temperature on λ_{lam} is taken into account by the formula

$$\lambda_{lam} = \frac{64}{Re}\sqrt{\frac{\nu'}{\nu}}, \quad (4.8)$$

where Re is the Reynolds number based on average fluid viscosity; ν' — fluid viscosity corresponding to the average wall temperature; ν — average fluid viscosity.

For turbulent fluid flow in circular straight lines, the frictional head losses are [4] /100

$$h_f = \lambda_{tur}\,\frac{l}{4R_h}\,\frac{v^2}{2g}, \quad (4.9)$$

where R_h is the hydraulic radius, defined by the relation

$$R_h = \frac{F}{\chi}. \quad (4.10)$$

Here F is the tube section area (open area); χ — wetted perimeter.

The tube hydraulic radius:

(a) for circular section

$$R_h = \frac{\pi D^2}{4\pi D} = D/4; \tag{4.11}$$

(b) for rectangular section with sides a and b

$$R_h = \frac{ab}{2(a+b)}; \tag{4.12}$$

(c) for square with side a

$$R_h = a/4. \tag{4.13}$$

The following formula can be used to find the friction resistance coefficient [4]

$$\lambda_{tur} = \frac{1}{(1{,}81 \lg Re - 1{,}5)^2} \tag{4.14}$$

or the Blasius formula can be used [11]

$$\lambda_{tur} = \frac{0{,}3164}{\sqrt[4]{Re}}. \tag{4.15}$$

Formulas (4.14) and (4.15) are used for so-called technically smooth tubing, i.e., tubing in which the roughness of the internal surfaces is so small that it has practically no effect on the resistance. Such technically smooth tubing includes seamless tubing used in aircraft practice made from nonferrous and ferrous metals.

For flexible rubber-fabric hoses [5], the empirical formula is

$$\lambda_{ho} = 0.011 + 0.917\ Re^{-0.41}, \tag{4.16}$$

and for rubberized hoses reinforced internally with wire

$$\lambda_{ho.a} = \lambda_{ho} + \frac{16\delta^2}{Dl} \qquad (4.17)$$

where λ_{ho} is the resistance coefficient calculated using (4.16), δ — local roughness height in mm, l — wire spiral pitch in mm; D — hose internal diameter in mm.

The local head losses due to local changes of tubing shape and dimensions are defined in terms of the local resistance coefficient

$$h_l = \xi_m \frac{v^2}{2g} \qquad (4.18)$$

or

$$\Delta p_l = \xi_l \frac{v^2}{2g} \gamma = \xi \rho \frac{v^2}{2} \qquad (4.19)$$

where h_l are the head losses in fluid column height units, ξ_l — the local resistance coefficient, established experimentally; γ — specific weight of the fluid; Δp — head losses in pressure units. /101

The magnitude of the coefficient ξ_l is determined experimentally in most cases [3], for example:

(a) for gate valves;

ξ_l = 2.5 — 3.0 — with 90° change of fluid flow direction;

ξ_l = 0.5 — 1 — with flow direction change by a small angle or no flow direction change;

(b) for distribution and check valves ξ_l = 2 — 3;

(c) for tubing elbows which alter the flow direction by 90° smoothly the coefficient ξ_l can be determined from the curve shown in Figure 4.18 [3];

(d) for tees which divide and combine streams and also for elbows which deflect streams through various angles, the ceofficient ξ_l is shown in Figure 4.19 [3];

(e) for abrupt tubing expansion in the flow direction as a result of which the flow velocity decreases as the section changes, the coefficient $\xi_{l.exp}$ is determined from the formula

$$\xi_{l.exp} = (1 - F_1/F_2)^2, \qquad (4.20)$$

where F_1 and F_2 are the tubing internal section areas in the expansion segment $F_2 > F_1$.

The head losses due to abrupt tube section expansion can be reduced considerably by providing a diffuser, the optimum angle for round tubes being 7° — 9°.

Abrupt tube narrowing in the flow direction usually leads /102
to smaller head losses than abrupt expansion for the same area ratio F_2/F_1 in both cases. The resistant coefficient for abrupt line contraction is found from the formula

$$\xi_{l.con} = \frac{1}{2}\left(1 - \frac{F_2}{F_1}\right). \qquad (4.21)$$

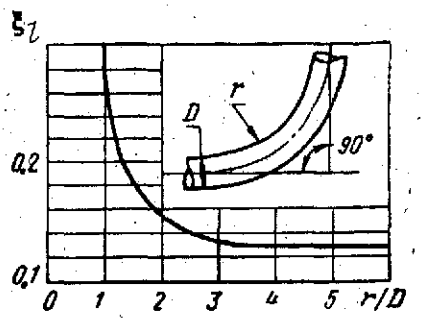


Figure 4.18. Local resistance coefficient ξ_l of tube elbow which alters fluid flow direction by 90° as function of relative bend radius r/D (from experimental data of [3]).

The overall head losses in the system are found by summing the pressure losses in the individual lines and tubing segments.

Electrical Energy Sources for ALSS

In the pressure suit LSS, the electric energy users are the fans, radio and telemetry equipment, pumps, instrumentation, and the pressure suit helmet faceplate heating elements.

In an emergency situation, it is obviously necessary that the LSS obtain electric energy continuously in the course of the entire time such a situation exists.

The pressure suit ALSS utilize electrochemical current sources (ECCS) — chemical batteries, galvanic and fuel cells, and also solar batteries.

On the basis of experience in using ALSS, the following requirements are imposed on the electric energy sources: reliability and safety of application, absence of effects harmful to the surrounding medium and to man (release of noxious gases and vapors, excessive heat emission, and so on), capability of operating under conditions of hard vacuum and weightlessness, lowest possible weight and size, retention of constant energy characteristics in the course of the specified time, the required mechanical strength, possibility of operating in any spatial position, and low internal resistance.

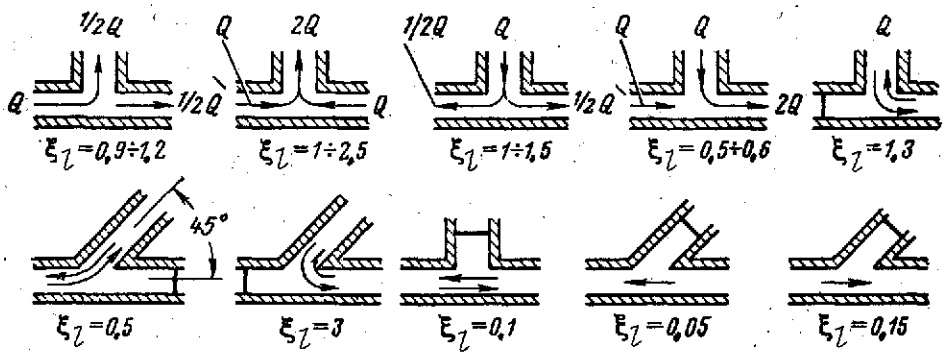


Figure 4.19. Various types of tubing tees and magnitudes of their local resistance coefficients ξ_l (from experimental data).

Electrical batteries are reusable chemical sources of electrical energy, while galvanic cells are not capable of further operation after discharge.

Electrochemical current sources are characterized by their electrical and operational characteristics. The former include: emf and voltage, internal resistance, capacity, energy output, self-discharge magnitude. The latter characteristics include service life, operational duration, and working temperature range. Let us examine in more detail some of these ECCS characteristics. Usually the ECCS output capacity is determined with constant discharge current I_d in the course of a time such that the voltage drops to its minimum permissible value.

Under these conditions, the deliverable output is

$$Q = I_d \int_0^\tau u d\tau = \frac{u_i + v_f}{2R_l} \tau, \qquad (4.22)$$

where u_i and u_f are the initial and final voltages, R_l — external circuit load resistance, τ — ECCS discharge duration. The ECCS energy output for constant discharge current I_d is

$$W = I_d \tau u_{av} = \frac{u_{av}^2}{R_l} \tau$$

where u_{av} is the average voltage during the discharge time.

The deliverable capacity and energy output of a specific ECCS decrease markedly with increase of the discharge current rate or reduction of the discharge duration. Therefore, the ECCS model should be selected on the basis of the specified discharge regime (discharge duration or discharge current intensity). /103

Moreover, the choice of ECCS type must be correlated with its per-unit-weight capacity and energy output: $Q_G = Q/G$ A/h/kG, $W_G = W/G$ W/h/kG, and also with the specific volumetric capacity and the specific volumetric energy output $Q_V Q/V$ A/h/dm^3 and $W_V W/V$ W/h/dm^3, where Q is deliverable capacity in A/h; G — ECCS weight in kG; V — ECCS volume in dm^3.

These specific characteristics are presented in Table 4.9 for ECCS types produced in the USSR.

Many ECCS types with liquid electrolytes (water solutions of acids or alkalis) release gases during operation which present fire or explosion hazard and are harmful to man (hydrogen, sulfuric acid vapors, and so on). It is obvious that for such ECCS it is necessary to take special measures to localize these deficiencies and the possible emergency situations.

Moreover. these current sources must be sealed to prevent evaporation of their electrolytes and increase of the electrolyte density. The sealing system is equipped with a valve to

TABLE 4.9

SPECIFIC CHARACTERISTICS OF ELECTROCHEMICAL CURRENT SOURCES MANUFACTURED IN THE USSR [6]

Current source name and designation	Specific characteristics			
	By volume		By weight	
	A/h/dm^3	W/h/kG	A/h/kG	W/h/dm^3
Primary current sources (galvanic cells)				
Manganese-zinc battery 3.7 FMTs-0.5 (pocket flashlight battery)	12.5	15	6.6	8
Flashlight cell MTs	63	76	38	46
Manganese-magnesium cell (in slow discharge regime)	130	200	64	97
Mercury-oxide cell OR	270	300	62	68
Zinc-chloride cell	70	127	27	46
Silver-magnesium cell	40	61	37	55
Silver-zinc cell (in starter discharge regime)	130	200	48	70
Manganese-air-zinc cell (in slow discharge regime)	91	105	46	55
Secondary current sources (batteries)				
Lead-acid (aviation type)	39	58	16	26
Plate-type Ni-cad alkaline	36	43	13	16
Plateless Ni-cad alkali	54	65	32	38
Silver-zinc	160	260	80	120
Silver-cadmium	172	220	38	53

release the gases which evolve. At the same time, the valve must not permit formation of negative pressure (vacuum) in the ECCS case.

A significant drawback of the chemical current sources is /104
their capacity loss in the course of time in the absence of external load because of self-discharge, the magnitude of which is determined from the relation

$$C = \frac{Q_i - Q_{st}}{Q_i} \cdot 100, \qquad (4.23)$$

where Q_i is the initial (nominal capacity, Q_{st} — capacity after storage.

Data on the magnitude of the self-discharge of some ECCS produced in the USSR are shown in Table 4.10.

The discharge characteristics become very important at low temperatures, since the deliverable capacity and energy output decrease (Figure 4.20) for all ECCS (without exception) with reduction of the temperature of the active mass and electrolyte.

Silver-zinc batteries, which differ from the conventional alkali or acid batteries (Figure 4.21), are most widely used on flight vehicles (FV).

The size and weight characteristics of various types of silver-zinc batteries are shown in Tables 4.11, 4.12, and 4.13.

The limiting positive temperature for silver-zinc batteries is 50° C. Their electrolyte is an aqueous solution of chemically pure potassium hydroxide with density 1.4. When using silver-zinc batteries in vacuum, they are placed in a hermetic housing equipped with a valve for discharge of the gases evolved by the battery during operation.

In contrast with silver-zinc batteries, the silver-cadmium batteries permit sealing and are suitable for operation in vacuum without an additional case.

TABLE 4.10

EXPERIMENTAL DATA ON MAGNITUDE OF SELF-DISCHARGE OF SOME ELECTROCHEMICAL CURRENT SOURCES PRODUCED IN THE USSR [6]

Current source	Self-discharge in %	
	Electrolyte temperature in °C	
	+40	+20
Manganese-zinc cells and disc-type and cup-type FMTs batteries	—	25 — 30% after 4 — 12 months
Mercury-oxide cells	—	about 10% after 1 yr
Lead-acid batteries	—	21% after 30 days
Nickel-iron battery	100% after 30 days	18 — 35 % after 30 days
Plate-type Ni-cad battery	23% after 30 days	11 — 18% after 30 days
Plateless Ni-cad battery	20 — 22% after 30 days	15% after 30 days
Silver-zinc battery	100% after 55 days at +35° C	30% after 6 months

Fuel cells are electric energy sources in which the chemical energy of the fuel is converted directly into electrical energy, bypassing the usual stages in generation of electrical energy by thermal machines: /105

— burning of the fuel to convert its chemical energy into thermal energy;

— conversion of the thermal energy into mechanical energy by means of a heat engine;

— conversion of the mechanical energy into electrical energy by means of electric generators.

In regard to operating principle, the fuel cells also are electrochemical current sources. At the present time, it is possible with the aid of hydrogen-oxygen fuel cells to convert

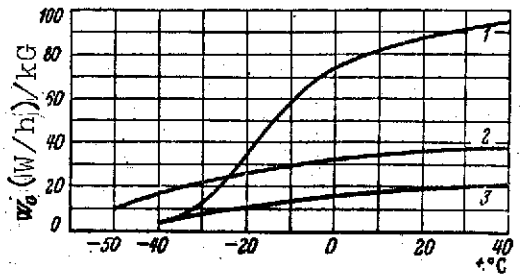


Figure 4.20. Experimental temperature dependence of per-unit-weight energy output (10-hour discharge to voltage of 1 V for alkali and 1.7 V for acid sources) of electrochemical current sources [7].

1 — silver-zinc batteries; 2 — plateless Ni-cad batteries; 3 — plate-type Ni-cad batteries.

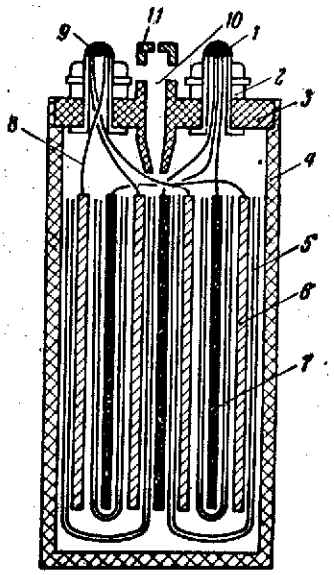


Figure 4.21. Construction of silver-zinc battery [6].

1 — positive terminal; 2 — terminal nut; 3 — cover; 4 — case; 5 — negative electrode separator; 6 — negative electrode; 7 — positive electrode; 8 — current lead; 9 — negative terminal; 10 — filling hole; 11 — plug.

about 70% of the chemical energy contained in them into electrical energy. Theoretically, this figure can be raised to 90%.

The basis of the fuel cell working process is the reaction of electrochemical combination of hydrogen with oxygen, in which a large portion of the chemical energy is converted into electrical energy. /106

A schematic of a fuel cell is shown in Figure 4.22. Two tubular porous electrodes made of hydrogen-metal mixtures are located in a container filled with the electrolyte (for example, a KOH solution).

Table 4.11

SIZE AND WEIGHT OF STsK SILVER-ZINC BATTERIES PRODUCED IN THE USSR

Designation*	Dimensions, mm			Weight, g	
	Length	Width	Height with terminals	Without electrolyte	With electrolyte
STsK3	43	18	77.5	85	105
STkS18	49	34	116.5	275	345
STkS25	49	49	137.5	450	555
STkS40	55	51.5	159	620	785
STkS45	55	51.1	159	630	800
STkS50	65	50	162	750	985

*Numerals indicate capacity in A/h.

The gaseous hydrogen and oxygen, diffusing through the electrode walls, interact with the electrolyte ions. As a result, free electrons accumulate on the hydrogen electrode and an electrical current develops in the external load R_l.

Experience in the use of *solar batteries* on spacecraft has shown that they are quite reliable and stable electric energy sources.

It has been suggested in the literature that solar batteries /107 can be used as electric energy sources for pressure suit LSS, however, no information has yet appeared on actual models of such batteries.

Protective coatings made from organic polymers, and also high-strength inorganic coatings have been developed to improve the service life and reduce heating of solar batteries.

TABLE 4.12

SIZE AND WEIGHT OF STsS SILVER-ZINC BATTERIES PRODUCED IN THE USSR

Designation	Dimensions, mm			Weight, g	
	Length	Width	Height with terminals	Without electrolyte	With electrolyte
STsS3	43	18	77.5	85	105
STsS5	46	33	81.5	150	180
STsS12	48.5	22.5	115.5	190	225
STsS15	48.5	28.5	115.5	225	275
STsS18	49	34	116.5	275	335
STsS25	49	49	137.5	450	545
STsS40	55	51.5	159	620	785
STsS50	65	50	162	750	985
STsS70	93	51.5	168	1050	1450
STsS100	108	51.5	168.5	1400	1750
STsS120	71	55	239.5	1600	1985

TABLE 4.13

SIZE AND WEIGHT OF STsD SILVER-ZINC BATTERIES PRODUCED IN THE USSR

Designation	Dimensions, mm			Weight, g	
	Length	Width	Height with terminals	Without electrolyte	With electrolyte
STsD3	43	18	77.5	95	110
STsD5	46	33	81.5	165	200
STsD12	48.5	22.5	115.5	190	230
STsD15	48.5	28.5	115.5	230	280
STsD18	49	34	116.5	295	360
STsD25	49	49	137.5	450	540
STsD40	55	51.5	159	750	825
STsD50	65	50	162	810	990
STsD70	93	51.5	168	1225	1505

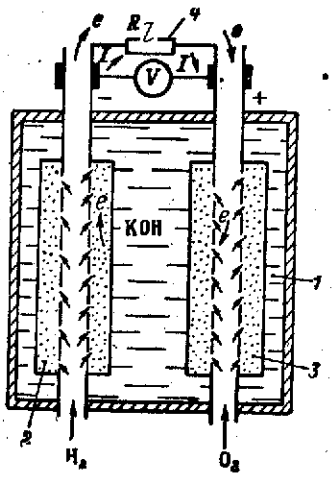


Figure 4.22. Schematic of fuel cell [6].

1 — electrolyte (water solution of KOH); 2 — hydrogen negative electrode; 3 — oxygen positive electrode; 4 — external load.

Along with their advantages, solar batteries also have several significant drawbacks:

1. They require a large surface area oriented perpendicular to the direction of solar ray incidence, as we see from the power formula

$$S=\frac{1}{\eta}\frac{W}{I_0}M_2, \qquad (4.24)$$

where S is the surface area; W — required battery power in W; I_0 — solar constant in $W/m^2/h$; η — efficiency.

In near-Earth orbit (or on the Moon), for

$$I_0 = 1200 \text{ kcal/m}^2\text{/h} \quad (1 \text{ kW/h} = 860 \text{ kcal})$$

or

$$I_0 = 2100/0.860 \approx 1400 \text{ W/m}^2\text{/h};$$

and $\eta = 0.10$

$$S=\frac{1}{0{,}1\cdot 1400}W=\frac{W}{140}\text{ m}^2.$$

2. Inadequate precision of battery orientation relative to the Sun.

3. The battery cannot operate without solar illumination.

It has been reported in the literature that some foreign firms have managed to fabricate solar batteries by bonding them to polyamide film which can be rolled up when not in operation.

Solar batteries of the foreign firms with thin-film converters have specific weight 4.55 g/W with efficiencies up to 8%.

Exhaled Air Regeneration in Pressure Suit LSS

The process of exhaled air regeneration in pressure suit LSS reduces to absorption of the carbon dioxide and other contaminants from the exhaled air.

Required for regeneration are substances (sorbents) which release oxygen when they react with carbon dioxide and water vapor.

Such substances are characterized by the:

— *respiratory regeneration coefficient,* which is the amount of sorbable carbon dioxide per unit oxygen volume,

$$a_{resp} = V_{CO_2}/V_{O_2},$$

where V_{CO_2} is the amount of carbon dioxide absorbed by a kilogram of the substance in the course of one minute; V_{O_2} — amount of oxygen released in the course of one minute;

— *the absorber utilization coefficient,* which depends on canister construction (in practice usually equal to 0.7 — 0.8);

— *the absorption coefficient,* which is the amount of sorbable carbon dioxide per unit sorbent weight, for example for $Ca(OH)_2$:

$$\varphi = \frac{M_{CO_2}}{M_{Ca(OH)_2}} = \frac{44}{74} = 0{,}59,$$

where M_{CO_2} and $M_{Ca(OH)_2}$ are the molecular weights;

— *the conversion coefficient*, which accounts for the sorbent properties

$$K_{con} = \varphi\zeta$$

where ζ is an experimentally determined coefficient, usually taken in the range 0.8 — 0.7;

— *the heating capacity*, i.e., the amount of heat released by the material (sorbent) in the reaction process.

Experimental studies have shown that sorbents in the form of peroxide compounds also have the ability to remove to a certain degree bacteria and certain impurities which are harmful to man from the air being regenerated.

It should be noted that, if there are several substances in the air being regenerated which simultaneously interact with the sorbent being used, the total amount of the substances absorbed by the sorbent will be considerably less than in the case of isolated interaction of the sorbent with each of the substances. Certain sorbents cannot be regenerated after use; others can be regenerated.

The nonregenerable sorbents, i.e., those which cannot be restored, are replaced by new sorbents after use. As nonregenerable sorbents, we can use the hyperperoxides and peroxides of the alkali metals and lime absorbers, which contain oxygem in the chemically bound state. The known nonregenerable sorbents are listed in Table 4.14.

TABLE 4.14

NONREGENERABLE SORBENTS FOR REGENERATING AIR, ABSORBING CARBON DIOXIDE, AND OBTAINING OXYGEN

(SEE CHAPTER 2 OF [5] AND CHAPTER 3 OF [2])

Sorbent	Chemical formula	Amount of active oxygen		CO_2 Absorptivity l/kG
		%	l/kG	
Sodium hyperoxide	NaO_2	43	300	200
Potassium hyperoxide	KO_2	33	200	150
Lithium hyperoxide	LiO_2	61,5	430	290
Lithium peroxide	Li_2O_2	35	240	380
Sodium peroxide	Na_2O_2	20	140	290
Potassium peroxide	K_2O_2	14,5	100	200
Calcium hydrate	$Ca(OH)_2$	—	—	150—200
Sodium chlorate	$NaClO_3$	—	200—250	—
Lithium hydroxide	LiOH	—	—	300—400
Sodium hydroxide	NaOH	—	—	—
Lithium oxide	Li_2O	—	—	200—450
Sodium ozonide	NaO_3	—	360	150

Sodium hyperperoxide (NaO_2) was discovered by Kazarnovskiy in 1936. It is obtained by the reaction

$$Na_2O_2+O_2=2NaO_2.$$

The stoichiometric content of active oxygen in NaO_2 is about 43%. During conversion to carbonate, NaO_2 absorbs about 200 liters/kG of CO_2 by the reaction

$$2NaO_2+CO_2+H_2O\rightarrow Na_2CO_3+H_2O+1{,}5O_2.$$

Potassium hyperperoxide (KO_2) contains about 33% oxygen. The carbon dioxide absorption during conversion to carbonate is about 150 liters/kG of substance. The bulk weight is 0.8 g/cm^3. KO_2 interacts energetically with water and water vapor

$$2KO_2+CO_2+H_2O\rightarrow K_2CO_3+H_2O+1.5O_2.$$

Sodium peroxide (Na_2O_2) is produced industrially. The active oxygen content is about 20%. Sodium peroxide reacts with moisture and carbon dioxide, forming hydroxide and sodium carbonate.

Potassium peroxide (K_2O_2) is a very unstable compound which oxidizes in air to potassium hyperperoxide.

Lithium hydroxide (LiOH) is used to absorb carbon dioxide /109 by the reaction

$$2LiOH+CO_2\rightarrow Li_2CO_3+H_2O+485 \text{ kcal/kG } CO_2. \qquad (4.25)$$

The water which forms in the reaction process remains partly in the absorber and is partly carried away by the gas stream flowing through the absorber.

Lithium hydroxide sorbs carbon dioxide at temperatures from +70 to -100° C.

Knowing the molecular weight of the substances appearing in (4.25), we can determine the absorption coefficient φ. For example, the weight of two gram molecules of LiOH is 48 g, and that of one gram molecule of CO_2 is 44 g. Consequently, the amount of LiOH necessary to absorb one kG of CO_2 will be

$$\varphi = \frac{M_{LiOH}}{M_{CO_2}} = \frac{48}{44} = 1.09 \text{ kG/kG } CO_2.$$

Depending on canister construction, sorbent properties, and sorbent working conditions, the magnitude of the conversion coefficient is $K_{con} = \varphi\xi = 1.09 \cdot 0.7 = 0.75$.

Lime absorbers are used to absorb carbon dioxide by the reactions

$$2NaOH + CO_2 = Na_2CO_3 + H_2O + 28 \text{ kcal}$$

or (4.26)

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O + 19 \text{ kcal}$$

The absorption coefficient φ for $Ca(OH)_2$ was determined above and is 0.59.

As a result of extensive testing, a lime chemical absorber /110
(LCA) composition was found which releases a small amount of heat [16]. Its composition in percent is: $Ca(OH)_2$ — 76.00; $MnSO_4$ — 2.66; $Fe(OH)_3$ + $Al(OH)_3$ - 1.20; NaOH — 1.83; moisture — 18.31.

The presence of several compounds ($MnSO_4$; Al, Fe, and so on) which play the role of catalyzers and cementing substances, prevents agglomeration of the absorbent.

In comparison with the hyperperoxides, *potassium ozonide* (KO_3) and *sodium ozonide* (NaO_3), obtained by passing a mixture of ozone and oxygen gases through a layer of solid metal hydroxide, are less stable and can be stored only at comparatively low temperature (about 0° C). We see from the data of Table

4.14 that, in regard to oxygen content, the ozonides surpass the hyperperoxides and peroxides.

Solid substances containing oxygen yield about 200-250 liters of gaseous oxygen per kilogram of substance when burned.

Such substances are the perchloric acid salts (perchlorates) and the chloric acid salts (chlorates).

The sodium chlorates are used to obtain oxygen. In this case, thermal decomposition of the chorate at temperature 700 to 800° C is used following the reaction

$$2NaClO_3 \rightarrow 2NaCl + 3O_2 + 232 \text{ kcal/kG}.$$

The theoretically possible oxygen yield is 45%, the actual yield is 40%. The heat required to maintain the reaction is created by oxidation of a small mount of iron powder mixed with the chlorate

$$2Fe + O_2 \rightarrow 2FeO + 885 \text{ kcal/kG}.$$

Ignition of the chlorate, prepared in candle form, can be accomplished by a phosphor match or electric squib.

In conclusion, we can note the following advantages of the air regeneration systems which store oxygen in the chemically bound form in comparison with the other systems:

— the quite broad temperature (20 ± 10° C), relative humidity (30 — 70%), and barometric pressure (760 ± 500 mm Hg) ranges in which the systems operate effectively;

— the capability for absorbing gaseous wastes released in the process of human activity;

— the capability to withstand vibrations and high load factors;

— thermal and explosive stability;

— simplicity of construction;

— minimum power required;

— high operating reliability;

— possibility of automating the process for creating the required microclimate conditions;

— possibility of unlimited long-term oxygen storage.

Contaminant absorbents are used in portable ALSS planned for extended operation. Usually they are introduced into canisters along with the CO_2 absorbent and anti-aerosol filters in order to absorb contaminants, specifically CO, from the gaseous mixtures.

The CO is oxidized with CO_2 with the aid of hopcalite catalyzers, usually consisting of four (30% CrO; 50% MnO_2; 15% Cu_2O_3, and 5% Ag_2O) or two (60% MnO_2 and 40% CuO) components. The active component is manganese perioxide (MnO_2), the other components play the role of promoters, i.e., substances which intensify the catalytic capability of the active component. /111

Hopcalite is prepared in the form of grains of dimensions 2.5 — 3.5 mm, the bulk weight of hopcalite is 1.1 kG/liter.

The catalytic action of hopcalite terminates at negative air temperatures. Because of the fact that water vapor has an adverse effect on hopcalite, the latter is placed between two layers of dessicant in the canister.

Oxidization of CO in hopcalite is accompanied by the release of a considerable amount of heat and takes place by the reaction

$$2CO+O_2 \rightarrow 2CO_2+136 \text{ kcal/kG CO,} \qquad (4.27)$$

which, in certain cases, may lead to canister damage. One technique for reducing the heat is to mix the hopcalite with aluminum.

Activated charcoal is a widely used absorbent of various contaminants.

Activated charcoals are wood charcoals which have been subjected to special treatment to increase their adsorbing surface area,* and remove resinous substances from their pores. The activated charcoals differ in grades and technical characteristics, among which the magnitude of the charcoal active surface varies from 600 to 1700 m^2/g. When charcoal is moistened, its activity diminishes.

The specific weights of the activated charcoals vary as a function of charcoal grade [8], for example, true specific volumetric weight** from 1.75 to 2.1 kG/dm^3, apparent specific weight*** from 0.5 to 1.0 kG/dm^3, and specific volume, bulk or gravimetric weight**** from 0.2 to 0.6 kG/dm^3.

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*Adsorption is the absorption of molecules, atoms, or ions of certain substances from the surrounding medium by the surface of another substance, termed the adsorbent.

**Weight of unit charcoal volume without account for the pores present in the charcoal.

***Weight per unit porous charcoal volume.

****Weight of unit charcoal layer volume, including the volume of the pores and spaces between the charcoal particles.

Regenerable adsorbents are substances whose absorbing capacity can be restored after usage by one technique or another.

Various sorts of molecular sieves, i.e., substances in which the pore dimensions are commensurate with the molecule dimensions, can be used as regenerable adsorbents. During adsorption in these substances, the smaller molecules are separated from the larger molecules. Certain activated charcoals and porous glasses, particularly porous alumosilicate crystals such as the natural and synthetic zeolites (pore entrance diameter from 4 to 9 Å) — have this capability.

The physical characteristics of the granulated synthetic zeolites are shown in Table 4.15.

Zeolites are normally used in the form of granules consisting of crystalline powders and binders (10 — 15%).

An important property of the zeolites is their capability for self-regeneration in vacuum for subsequent reuse.

Table 4.16 presents data characterizing the adsorption capability of various regenerable substances [9].

There are also liquid regenerable CO_2 absorbers. Brief information on some of them is shown in Table 4.17.

The liquid absorbers can be regenerated quite well at /113
pressures of 1 — 2 mm Hg and normal temperature (20 — 30° C), however, their application is difficult under weightless conditions.

TABLE 4.15

PHYSICAL PROPERTIES OF GRANULATED SYNTHETIC ZEOLITES NaA, CaA, Cax, Nax [10]

Physical properties	Value	Physical properties	Value
Bulk weight:		Max water adsorptivity	0.25 cm^3/g
powder	0.52 g/cm^3	Dynamic activity with respect to CO_2 (with initial CO_2 concentration 0.05%)	4—6 g/100 g
granules (d = 1.6 mm)	0.685 "		
granules (d = 3.2 mm)	0.715 "	Thermal stability with multiple regeneration	300—400°C
porosity	50—60%	Max thermal stability in case of short-term (to 6 hours) reheating	600—750
Pore entrance diameter:			
Zeolite NaA	4 Å	Heat of water desorption	1000—1200 cal/g
Zeolite Cax	5 "		
Zeolite Cax	8 "	Crushing strength of whole tablets	7.5—10 kG per tablet
Zeolite Nax	9—12 Å		
Sp. heat	0.25 kcal/kG/°C		

It has been established experimentally that thin membranes (films) which are permeable to gases but for which the rate of permeation through them is different for different gases can be used as adsorbents. The diffusional properties of the films depends on their thickness and molecular structure, the physical properties of the molecules of the permeating adsorbable gases, and their temperature. An important characteristic of the thin films is their selectivity in relation to the various gases. This capability can be utilized for the absorption of CO_2 and other gases and vapors.

The configuration of an absorption canister is shown in Figure 4.23. The canister metal body 7 is made of 0.5-mm thick brass with protective nickel coating. In the canister inlet throat there is a gas flow spreader 3 attached to the grid 4.

TABLE 4.16*

CO_2 ADSORPTION CAPABILITY OF CERTAIN SOLID SUBSTANCES AT VARIOUS TEMPERATURES [9]

Adsorbent	CO_2 partial pressure mm Hg	Adsorptivity in % of adsorbent weight at temperature in ° C						Adsorptivity in % of corresponding charcoal activity at temperature in °C					
		−78	−17	0	20	50	80	−78	−17	0	20	50	80
Activated charcoal SKT	50	30,0	5,2	4,0	2,0	1,0	0,6	100	100	100	100	100	100
Silicagel KSM	50	5,0	0,8	0,4	0,3	0,2	0,1	17	15	10	15	20	17
Zeolite 4 Å	50	16,0	12,6	11,4	9,0	7,5	6,0	53	242	285	450	750	1000
Zeolite 5 "	50	22,2	16,7	15,7	13,8	7,6	5,0	74	322	392	690	760	835
Activated charcoal SKT	300	54,0	17,3	12,2	7,3	4,4	2,4	100	100	100	100	100	100
Silicagel KSM	300	9,8	2,4	1,5	0,8	0,4	0,2	18	14	12	11	9	8
Zeolite 4 Å	300	18,2	15,6	14,4	12,4	11,3	10,7	34	90	118	170	257	445
Zeolite 5 "	300	24,7	18,4	18,0	16,8	13,6	11,6	46	106	148	230	310	485

*Commas in the numbers indicate decimal points.

TABLE 4.17

ABSORPTION CAPABILITY OF LIQUID REGENERABLE CO_2 ABSORBERS

Absorber	Absorptivity, l(s)/kG
Monoethanolamine	153
Monoethanolethylenediamine	107
Polyethylenepolyamine	46
Diethanolamine	35

Gaskets 5 are located between the active material blocks. A filter is located at the canister outlet. The filter is enclosed between two grids 1. Springs 6 are provided between the blocks to force the blocks against the covers 8.

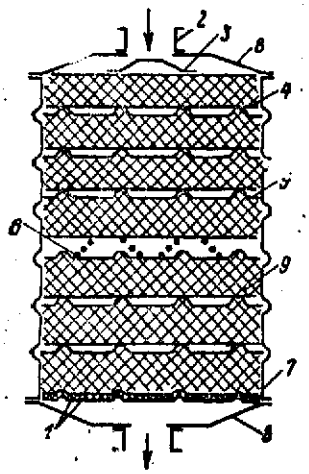


Figure 4.23. Absorber canister.

1 — filter grid; 2 — throat; 3 — gas flow spreader; 4 — grid; 5 — gasket; 6 — springs; 7 — filter body; 8 — filter cover; 9 — sorbent (chemical substance).

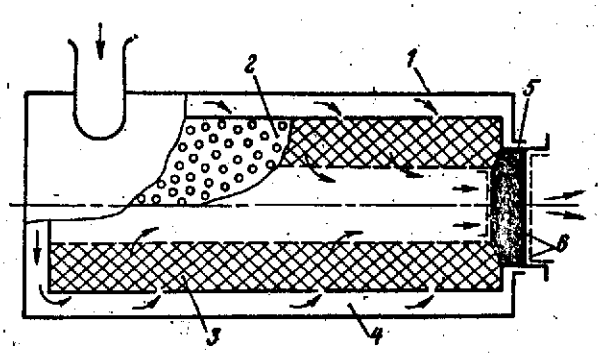


Figure 4.24. Absorber canister.

1 — outer case; 2 — perforated inner cylinder; 3 — sorbent; 4 — channel; 5 — activated charcoal for absorbing carbon monoxide; 6 — protective grid.

The clamping springs prevent the absorber grains from altering their relative position in the canister after it is charged, and thus prevent formation between the grains of fistular paths through which the larger portion of the air entering the canister could pass without being cleaned. The force developed by the spring is about 10 — 15 kG/dm^2.

Another design variant is the absorber canister shown in Figure 4.24. The canister consists of the outer case 1 inside which there is inserted the perforated cylinder 2. The gas containing CO_2 enters the canister and fills the space 4. Under /114 the influence of the pressure difference, the gas flows through the absorber 3.

The distinctive feature of this canister variant is the large contact surface area between the gas and the absorber and, consequently, better sorption.

The use of aluminum alloys to fabricate absorber canisters is not recommended because of the destructive action of many absorbents on these alloys.

The weight of the canister casing usually does not exceed 30 — 40% of the weight of the sorbent contained therein.

The sorbent effectiveness depends significantly on the thickness of the sorbent layer in the absorption canister. The greater the thickness of this layer and the longer the time of contact between the air being cleaned and the sorbent, the more effective is the sorbent utilization and, in the final analysis, the lower its weight. On the other hand, the canister hydraulic resistance dependence on sorbent thickness should be considered.

The thinner the sorbent layer, the lower is the canister hydraulic resistance, as is seen from the formula (for sorbent grain dimensions about 3 mm)

$$\Delta p_{can} = 1.18hW^{1.5} \text{ mm } H_2O \text{ (kG/m}^2\text{)}, \qquad (4.28)$$

where h is the sorbent layer thickness in cm; W is the specific loading in the canister section in liters(s)/min/cm^2.

In calculations of sorbent layer thickness, we must consider not only the specific loading in the section but also the required time of contact with the gas, determined from the formula

$$\theta = \frac{B_1}{W} h - B_2 \delta \frac{1}{\sqrt{W}}. \qquad (4.29)$$

where θ is the time of sorbent contact with the gas; B_1, B_2 — are experimentally determined constants of the given sorbent; δ — average sorbent grain size in mm.

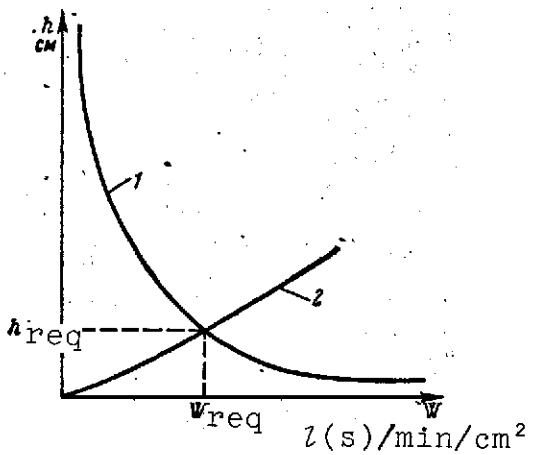


Figure 4.25. Curves for determining sorbent layer thickness h and specific load W in canister section. 1 — h(W) based on canister hydraulic resistance; 2 — h(W) based on required time of gas contact with sorbent.

Equations (4.29) and (4.30) are solved jointly for h graphically (Figure 4.25) and the solution of these equations yields values of h and W which satisfy the conditions of minimum absorber canister hydraulic resistance and weight.

In the absence of reliable values of the constants B_1 and B_2, we can take for approximate calculations values of W as a function of sorbent type ranging from 0.20 to 0.25 to 0.4 to 0.6 liters(s)/min/cm^2.

For values W > 1.0, there may be entrainment of small sorbent particles. Experience has shown that for good sorbent utilization, the thickness of its layer in the canister should not be less than 10 — 15 cm.

Example. Let us calculate the dimensions and hydraulic resistance of the CO_2 absorption canister variant shown in Figure 4.23 of pressure suit LSS with the following initial data: the absorbent is LiOH with effective absorbing capacity of about 400 liters(s) of CO_2 per kilogram and gravimetric (bulk) weight Δ = 0.8 kG/dm^3; subject CO_2 emission rate about 0.6 liters(s)/min; duration of continuous canister operation τ = 4 hours. /115

In the first approximation, we take h = 10 cm and W = 0.5 liters(s)/min/cm^2, then from (4.29) the pressure losses in the absorbent are $\Delta p_{abs} = 1.18 \cdot 10 \cdot 0.5^{1.5} = 6.25$ mm H_2O.

To this value of Δp_{abs} we must add the pressure losses at the inlet to and exit from the canister and the losses in the space between the absorbent layers (see Figure 4.23).

The total amount of CO_2 released in 4 hours is V_{cd} = 0.6·240 = 144 liters(s).

The absorber (sorbent) weight required to absorb the CO_2 is G_{abs} = 144/400 = 0.36 kG. With a 50% margin, this weight corresponds to the absorbent volume

$$V_{abs} = \frac{1.2\ G_{abs}}{\Delta} = 0.54\ dm^3$$

and canister section area

$$F_{can} = \frac{V_{abs}}{h} = 0.54/1.0 = 0.54\ dm^2\ (d_{can} = 0.83\ dm).$$

The resulting value of F_{can} must agree with the actual specific loading in the canister section, determined from the total amount of air passing through the canister.

For the assumed value W = 0.5 liters(s)/min/cm^2, the amount of air passing through the canister is

$$Q = WF_{can} = 0.5 \cdot 54 = 27\ \text{liters(s)/min}, \qquad (4.30)$$

or, reducing to the pressure in the pressure suit system

$$\Delta p = 160\ \text{mm Hg},\ Q = 27(760/160) = 128\ \text{liters(s)/min}.$$

If this amount is not adequate on the basis of ventilation conditions, either W or F_{can} is increased accordingly within the limits of the admissible values.

Usually this problem is solved by successive approximation and the solution results are checked experimentally.

Fans

The fans used in pressure suit LSS must have high reliability, the highest possible efficiency, and the lowest possible weight and size. They must be noiseless and operate in an oxygen atmosphere.

A distinctive feature of such fans is the relatively low air flowrate (150 — 300 liters(s)/min).

The fan head, determined by the total resistance of the entire system, usually does not exceed 100 — 250 mm H_2O (100 — 250 kG/m^2).

The connection between fan output and pressure developed by the fan for a definite rpm and various system resistances is usually expressed in graphical form and is termed the individual fan characteristic.

In comparing various fan designs and also in constructing the dimensional characteristics of geometrically similar fans,* the following characteristics are used:

---

*Fans are considered geometrically similar if all the flow path dimensions of one of them can be obtained by multiplying by the same number the corresponding dimensions of the other fan.

— dimensionless output $\bar{Q} = Q/3600S_i U_i^2$;

— dimensionless pressure $\Delta\bar{p} = \Delta p/\rho U_i^2$;

— dimensionless power $\bar{N} = (N/\rho S_i U_i^3)102$,

where $S_i = \pi D^2/4$ is the area of a circle whose diameter is equal /116 to the fan impeller diameter in m^2; $U_i = \pi Dn/60$ — impeller tip velocity in m/sec; D — impeller diameter in m; n — impeller rpm; ρ — air density in $kG/s^2/m^4$; Δp — pressure (head) developed by the fan

$$\Delta p = p_2 - p_1 + \frac{\rho}{2}(v_2^2 - v_1^2).$$

Here p_1 and p_2 are the gage pressures at the fan inlet and outlet sections in kG/m^2; v_1 and v_2 — average velocities of the gas stream at the fan inlet and outlet sections in m/s.

Considering that $v_1 \approx v_2$, $\Delta p = p_2 - p_1$.

The power required by the fan is found from the formula

$$N = Q\Delta p/75\eta_{ov}, \qquad (4.31)$$

where η_{ov} is the fan system efficiency, $\eta_{ov} = \eta_f = \eta_{dr}$; here η_f is the fan efficiency and η_{dr} is the drive efficiency.

Fans are divided into centrifugal and axial. The choice of one or the other of these design variants is usually made on the basis of the value of the specific speed coefficient, termed the specific speed n_{sp}.

The specific speed for the optimum fan operating regime (for maximum efficiency) is found from the formula [11]:

$$n_{sp} = \frac{Q^{1/2} n}{\Delta p^{3/4}}. \qquad (4.32)$$

The coefficient n_{sp} can be considered a unique similarity criterion for a family of fans which have similar values of n, Q, and Δp. With the aid of this coefficient, we can make a preliminary selection of the values of these quantities using data obtained in testing a fan of an analogous family (type).

Geometrically similar fans have the same value of n_{sp} regardless of their dimensions, angular velocity, and the air density.

Centrifugal fans should be used for $n_{sp} < 100$ and axial fans for $n_{sp} > 100$ [11].

The axial fans usually have a high efficiency (there are no energy losses associated with flow turning) and they are more compact and are reversible.

Centrifugal fans have an impeller 1 (Figure 4.26) with blades, shaft 6, and casing with diffuser 2 which isolates the impeller from the external medium.

The opening in the casing through which the impeller shaft passes is equipped with the seal 5.

Diffusers are usually made of two types — with and without guide vanes.

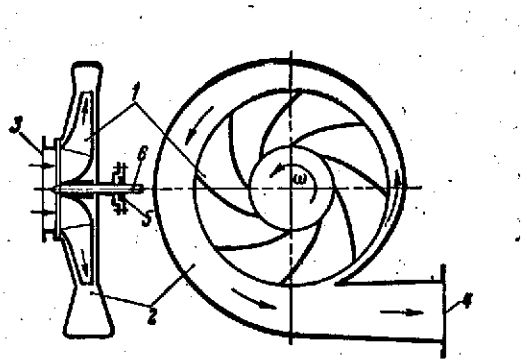


Figure 4.26. Schematic of centrifugal fan.

1 — impeller; 2 — case and diffuser; 3, 4 — inlet and outlet; 5 — seals; 6 — shaft.

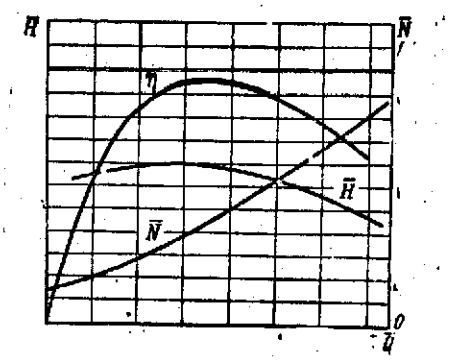


Figure 4.27. Dimensionless characteristics of centrifugal fan.

η — efficiency; $\bar{N}$, $\bar{H}$, $\bar{Q}$ — dimensionless fan characteristics.

As the impeller rotates, the velocity of the incoming air is increased and the air is compressed under the action of centrifugal forces. In the diffuser, the kinetic energy of the air is converted into pressure energy as a consequence of smooth increase of the section area in the air flow direction.

Characteristic of centrifugal fans is higher impeller rotational speed (10,000 — 35,000 rpm). Therefore, they have comparatively large output even with small dimensions. Usually /117 the impeller diameters of ALSS fans are very small and do not exceed 8 — 15 cm.

In order to increase efficiency and reduce noise, the fan blade tips are swept somewhat in the direction opposite the angular velocity, as shown in Figure 4.26 [11].

With reduction of the fan dimensions, its characteristics deteriorate. In selecting the design parameters of miniature fans, we should use the characteristics obtained in tests of geometrically similar minature fans. Figure 4.27 shows the fan

dimensionless characteristics which are normally used in fan selection.

In the case of proportional change of the fan geometric dimensions, scaling formulas are used to obtain the characteristics if the specific speed of the fan which is altered in size is close to or equal to the specific speed of the original fan [11].

It should be noted that, with change of the air density, the fan head and power change but its volumetric output remains unchanged.

Fan characteristics are usually defined for standard conditions of air density ρ_0 (pressure 760 mm Hg and temperature 15° C), therefore, the fan head at the altitude H with the density ρ_H is calculated using the formula*

$$\Delta p_H = \Delta p_0 \rho_H / \rho_0, \tag{4.33}$$

while, for change of the air temperature only, we use the formula

$$\Delta p_H = \Delta p_0 T_H / T_0. \tag{4.34}$$

The diameter of the fan inlet opening is determined from the condition of minimum losses in the impeller [11]

$$D_0 = 1.65 \sqrt[3]{Q/\omega}, \tag{4.35}$$

where w is the impeller angular velocity of rotation in rad/sec.

To determine the impeller tip diameter and width, on the basis of statistical analysis of test results we can use the formulas [11] /118

* *Air humidity has very little influence on the value of the density; with humidity change from 0.5 to 1.0 the density changes by only 0.5%.

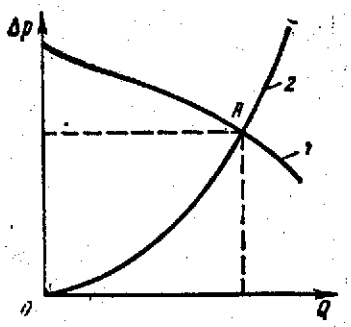


Figure 4.28. Combined air duct and fan characteristics.

1 — fan characteristics;
2 — air duct characteristic;
A — operating point.

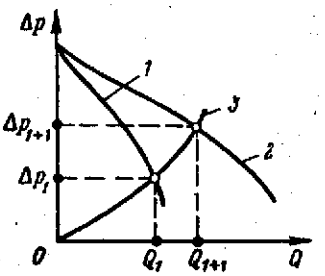


Figure 4.29. Overall characteristic of two identical (with respect to Q and Δp) fans connected in parallel.

1 — characteristic of a single fan; 2 — combined characteristic of two fans; 3 — characteristic of air ducting (subscript 1 indicates a single fan, subscript 1 + 1 — two identical fans).

$$D = D_0 \frac{60}{n_{sp}}; \qquad (4.36)$$

$$b = (0.3 \div 0.6) D_0, \qquad (4.37)$$

where D is the impeller outer diameter and b — impeller width.

From statistical data, for fans with specific speed n_{sp} = 20 — 55 η_{max} = 0.5 — 0.65 for blades whose tips are swept forward, η_{max} = 0.65 — 0.7 for blades which terminate radially, and η_{max} = 0.8 — 0.9 for blades whose ends are swept back.

The combined characteristics of the air duct and fan make it possible to determine from the point of intersection of the curves (operating point) the fan output and the magnitude of the head developed by the fan (Figure 4.28).

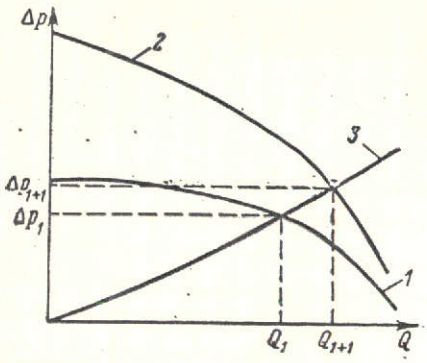


Figure 4.30. Combined characteristic of two series connected fans which are identical in output and head.

1 — characteristic of a single fan; 2 — combined characteristic of two fans; 3 — characteristic of air ducting system (subscripts same as in Figure 4.29).

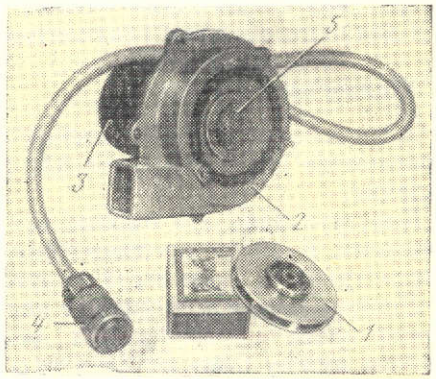


Figure 4.31. Small centrifugal fan.

1 — impeller; 2 — case; 3 — electric motor; 4 — electrical connector; 5 — air intake port.

In certain cases, several fans connected in parallel or series may be used to supply air to a common ducting system.

The combined characteristic of two identical (in output and head developed) fans operating in parallel into a single ducting system is shown in Figure 4.29.

In the series connection case, the fans are installed one behind the other and all the air passes through each fan. In constructing their combined characteristic, their pressures must be added (Figure 4.30).

Figure 4.31 shows a miniature fan with electric motor.

The fan impeller is made from aluminum alloy, the blades together with the disk are fabricated from an integral forging (stamping).

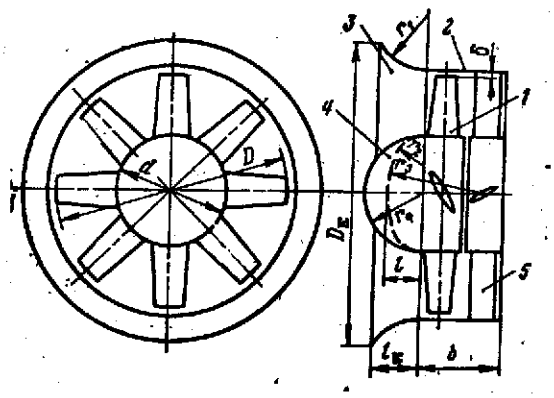


Figure 4.32. Schematic and basic dimensions of axial fan.

1 — impeller; 2 — cylindrical case; 3 — intake; 4 — fairing; 5 — straightening vanes.

The axial fan is a bladed wheel in a cylindrical casing. As the wheel rotates, the air entering through the inlet opening is compressed and its pressure is increased (Figure 4.32).

In accordance with GOST 11442-65 and GOST 10616-63, the basic dimensions of the axial fans shown in Figure 4.32 are connected by the following relations: $d = 0.3 - 0.55\ D$, $D_1 \leq 1.2\ D$, $l_1 = 0.2\ D$, $l = 0.25\ d$, $r_1 = 0.26\ D$, $r_2 = 0.75\ l$, $r_3 = 4l$, $r_4 = 0.5\ d$; b is taken as 20, 25, 30, 35, 40, 50, and 60% of D. /120

To increase output, the axial fans are connected in parallel or in series. In this case, the overall characteristics of the combined axial fans are determined just as for centrifugal fans.

Liquid Pumps

Liquid pumps are used in pressure suit LSS for forced circulation of liquid in the cooling loops.

In construction, these pumps may be centrifugal or gear types. Both are subject to the same general requirements as are the fans examined above.

In their operating principle, *the centrifugal liquid pumps* are analogous to the previously described centrifugal fans, with the constructional differences between them being the result of differences in the physical properties of the working fluids used in them.

The characteristics of centrifugal liquid pumps are defined just as the characteristics of centrifugal fans.

The efficiency of centrifugal liquid pumps (without account for motor efficiency) is usually 0.7 — 0.85, being somewhat lower for pumps of small output.

The power required by the pump is found from the well-known formula

$$N_r = \gamma QH/75\eta_{ov}, \qquad (4.38)$$

where γ is the specific weight of the liquid in kG/m^3; Q — the pump output in m^3/s; H — total head in m; η_{ov} — pump system efficiency

$$\eta_{ov} = \eta_p \eta_{dr} \qquad (4.39)$$

(η_p is the pump efficiency, η_{dr} — drive efficiency).

The power of the pump drive electric motors is taken with some margin over the calculated value, the margin being defined by the coefficient 1.2 — 1.4.

Like centrifugal fans, the centrifugal liquid pumps are characterized by the specific speed n_s, defined by (4.32). Replacing in this formula Δp kG/m^2 by the head H in meters H_2O column, we obtain

$$n_s = 3.65 \frac{nQ^{1/2}}{H^{3/4}}. \qquad (4.40)$$

By analogy with centrifugal fans, the specific speed of centrifugal liquid pumps can be considered the similarity criterion for an entire family (type) of pumps. As a similarity criterion, it is the same for all pumps of a single family and permits determining in the design process the parameters of the required pump from the known characteristics of one pump of the given family.

The gear pumps have as the propulsor which displaces the liquid a pair of gears located in a casing (Figure 4.33).

As the gears rotate, the liquid coming from the inlet line fills the cavities between the teeth and travels together with the teeth to the opposite side of the pump, where the teeth of the other gear enter these cavities and force the liquid into the delivery line.

If the gears are identical in diametral dimensions and number of teeth, pump output can be determined approximately from the formula [12] /121

$$Q_{th} = 2\pi m b \omega D_p, \qquad (4.41)$$

where m is the gear meshing modulus in m; b — gear width in m; w — gear rotational velocity in rad/sec; D_p — gear pitch circle diameter in m.

With account for internal losses, the actual output of the gear pump, like any other pump, is $Q = \eta_0 Q_{th}$, where η_0 is the pump volumetric efficiency (usually $\eta_0 = 0.90 — 0.95$).

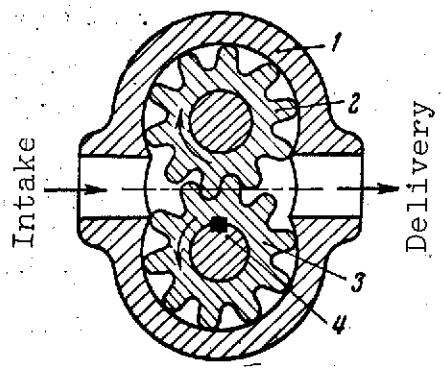


Figure 4.33. Construction of gear-type liquid pump. 1 — case; 2, 3 — gears; 4 — drive shaft.

Vessels for Storing Oxygen Supply

The onboard oxygen supply for flight vehicles is stored in bottles in the gaseous state or under high pressure, or in the liquid state in liquid oxygen gasifiers (LOG). The use of LOG of spacecraft is complicated by weightlessness, therefore in the pressure suit LSS at the present time, bottles are used to store the oxygen in the gaseous state. However, in the future, as systems for storing liquified gases are improved, LOG may also find application.

Oxygen bottles may be cylindrical or spherical and are designed for ambient working temperatures from -60 to +100° C. When it is necessary to use bottles at temperatures above 100° C, the condition must be observed:

$$p_t \leq p\sigma_t/\sigma, \qquad (4.42)$$

where p_t is the pressure at the specified elevated temperature, p — pressure corresponding to the temperature for which the bottle is designed, σ — ultimate strength of the material at the design temperature; σ_t — ultimate strength at the elevated temperature.

Depending on system mission, the oxygen bottles may be used only once or repeatedly.

The bottles of the repeated-use systems may be subject to pressure for an unlimited time, while in the single-use systems,

they are under pressure for only a limited (specified) time.

Repeated-usage bottles are normally used in the pressure suit LSS.

The wall thickness of the cylindrical and spherical bottles is found on the basis of strength conditions from the formulas:

$$\delta_{cyl} = r(p/\sigma) \text{ and } \delta_{sp} = (1/2)(p/\sigma)r \quad (4.43)$$

where r is the internal radius of the bottles with cylindrical and spherical surfaces; p — design pressure in the bottle; σ — design stress in the bottle wall material.

The burst pressure (p_{bur}) for bottle strength calculation /122 is determined as follows:

— for systems with unlimited time of bottle exposure to pressure $p_{bur} \geq 2.8\ p_{wor}$;

— for systems with limited time of bottle exposure to pressure $p_{bur} = 2.25\ p_{wor}$.

Bottles containing gases under high pressure can serve as energy sources (accumulators).*

The energy of compressed gases in bottles may be used to perform work as the gases expand and to absorb head because of the large gas temperature reduction as they expand.

*Knyazev, V. N. "Energy Output and Strength of High-Pressure Gas Bottles," Trudy Moskovskogo Aviatsionnogo Instituta, No. 143, Oborongiz, Moscow, 1961.

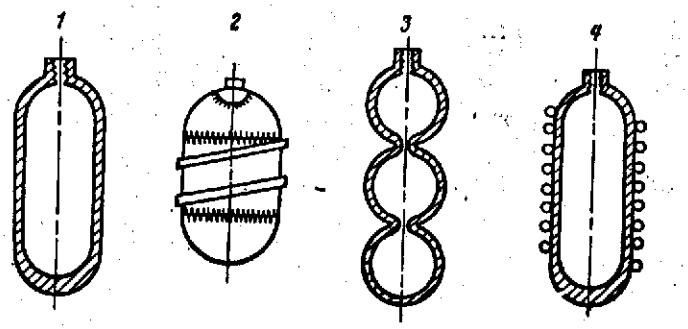


Figure 4.34. Oxygen bottle shapes.
1 — cylindrical (high-pressure); 2 — welded cylindrical (low pressure); 3 — spherical; 4 — cylindrical with exterior wrapping.

The high-pressure cylindrical bottles are usually made from lengths of thick-wall seamless tubing whose ends are transformed by hot forging into the bottom and throat (Figure 4.34). During forging, the thicknesses of the bottle bottom and throat increase significantly.

The spherical bottles are welded together from two stamped /123
(sometimes turned) halves.

Alloy steels (25 CrMnSiN, 12CrNi3N, and others) are used to fabricate the high-pressure bottles.

In order to reduce weight, bottles are made from thinner steel than is required on the basis of strength calculations and are reinforced by high-strength steel wire or glass-plastic wrapping wound on the bottle with high tension. Bottle weight is reduced more when using glass-plastic wrapping since the density of glass fiber saturated with epoxy resin and subjected to polymerization is nearly four times less than that of steel wire [24]. Specifically, the weight of two-liter capacity bottles with 420 kG/cm^2 operating pressure was calculated to

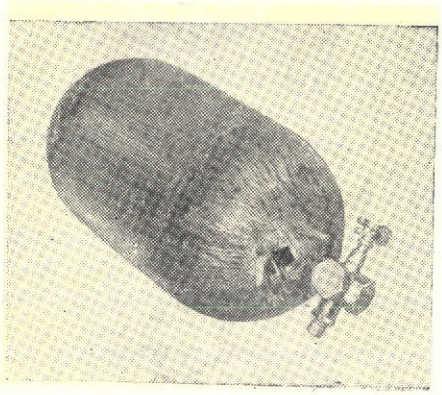


Figure 4.35. Welded cylindrical bottle with exterior glass-plastic wrapping (figure shows a puncture which did not lead to bursting of bottle subject to high pressure).

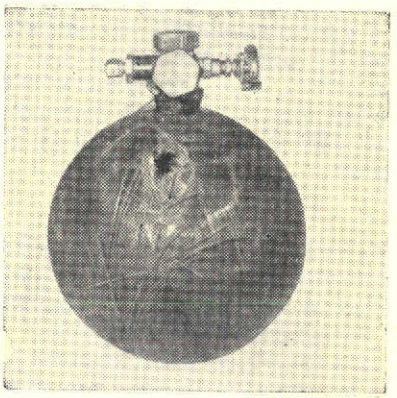


Figure 4.36. Spherical welded bottle (puncture can be seen in the picture).

decrease by 40% when replacing steel wire with glass-plastic wrapping (σ = 130 — 140 kG/cm^2). The weight of such a bottle, referred to unit weight of the oxygen stored in the bottle, amounts to 2 — 2.5 kG/kG O_2, with a strength margin of about 2.5 [25].

Welded bottles with glass-plastic wrapping are explosion proof when damaged by meteoric matter (Figures 4.35 and 4.36).

Weight data on bottles for storing compressed gases are shown in Table 4.18.

For not-very-high pressures and not-very-low temperatures, the weight of the gas in the bottle is usually determined using the well-know Clapeyron ideal gas equation pv = GRT. Real gases at high pressures and low temperatures do not follow this equation. These real gas deviations from the Clapeyron equation are caused, first, by the fact that real gas molecules have finite dimensions and, second, by the fact that there are interaction forces between molecules which increase markedly for very small distances between molecules.

TABLE 4.18**

WEIGHT DATA ON BOTTLES PRODUCED IN THE USSR FOR STORING COMPRESSED GASES*

Bottle volume in liters	Weight in kG at various working pressures in kG/cm^2				Bottle volume in liters	Weight in kG at various working pressures in kG/cm^2			
	150	200	350	400		150	200	350	400
1	1,3 / 1,0	1,8 / 1,4	— / 2,4	— / 2	3	3,5 / 2,9	4,7 / 3,8	— / 6,8	— / 7,5
2	2,5 / 1,8	3,3 / 2,4	— / 4,7	— / 5,2	8	9,0 / 7,9	12,7 / 10,3	— / 17,9	— / 19,4

*Numerator is cylindrical bottle weight; denominator is spherical bottle weight.

**Commas in the numbers indicate decimal points.

The graph of pv(p) in Figure 4.37 illustrates the deviations of some real gases from the ideal gas. It follows from the Clapeyron equation that pv = const for T = const, therefore the pv curve for an ideal gas with T = 273° K should lie parallel to the p coordinate axis, which is shown in Figure 4.37.

The equations accounting for the physical characteristics of real gases are complex and their solutions are usually obtained using tables and graphs of the functional relationships of the quantities appearing in the equations, which facilitate the calculations considerably.

Data on the degree of compressibility of air and oxygen as a function of temperature and pressure are shown in Tables 4.19 and 4.20. /124

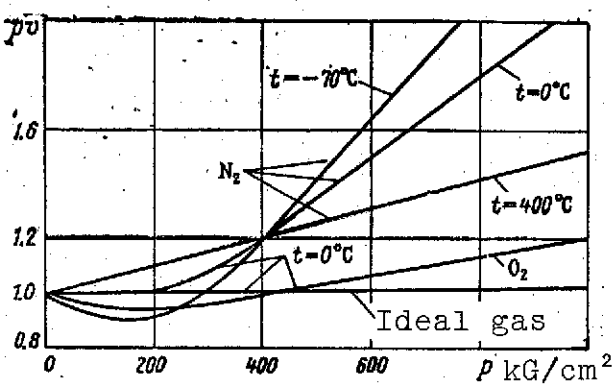


Figure 4.37. Curves characterizing deviations of properties of certain real gases (N_2 and O_2) from Clapeyron ideal gas equation.

Gasifiers for storing liquid oxygen have the following advantages over bottles for storing oxygen in the gaseous state under high pressure:

— reduced vessel physical volume because of the higher density of the liquified gas;

— reduced vessel weight as a result of the fact that low pressures can be used for the liquified gas;

TABLE 4.19*

DEGREE OF AIR COMPRESSIBILITY FOR DIFFERENT TEMPERATURES AND PRESSURES [21]

Air pressure kG/cm²	Air temperature in °C				Air pressure kG/cm²	Air temperature in °C			
	0	50	100	200		0	50	100	200
0	1,0006	1,1838	1,3669	1,7332	200	1,006	—	1,464	1,878
1	1,0000	1,1836	1,3669	1,7338	400	1,198	—	1,650	2,079
20	0,9899	1,1818	1,3707	1,7442	600	1,445	—	1,884	2,305
60	0,9775	1,1831	1,3823	1,7684	800	1,701	—	2,125	2,541
100	0,9710	1,1909	1,3989	1,7959	1000	1,951	—	2,376	2,785

*Commas in the numbers indicate decimal points.

— increased safety level associated with lower pressure in the vessels.

TABLE 4.20**

DEGREE OF COMPRESSIBILITY OF OXYGEN FOR DIFFERENT TEMPERATURES AND PRESSURES*

Pressure kG/cm²	Temperature in °C			Pressure kG/cm²	Temperature in °C		
	0	50	100		0	100	200
0	1,0010	1,842	1,3674	200	0,91	1,40	1,82
1	1,0000	1,1837	1,3672	300	0,96	1,45	1,89
10	0,991	1,180	1,366	400	1,05	1,53	1,96
20	0,982	1,175	1,365	500	1,16	1,62	2,05
40	0,965	1,167	1,363	600	1,27	1,72	2,14
60	0,949	1,161	1,363	700	1,39	1,83	2,24
80	0,936	1,156	1,363	800	1,50	1,93	2,34
100	0,923	1,152	1,365	1000	1,74	2,15	—

*Chemistry Handbook, Vol. 1, Khimizdat, 1951.

**Commas in the numbers indicate decimal points.

Along with the advantages, we should note the drawbacks of gassifiers:

— high sensitivity to heat influx from outside;

— some complication of the oxygen supply systems because of the equipment used to withdraw the oxygen from the vessel and convert it into the gaseous state.

The techniques for storing oxygen are determined by its physical state, namely:

— storage at supercritical pressure;

— storage in the two-phase state;

— storage of liquid oxygen in the single-phase state at subcritical pressure.

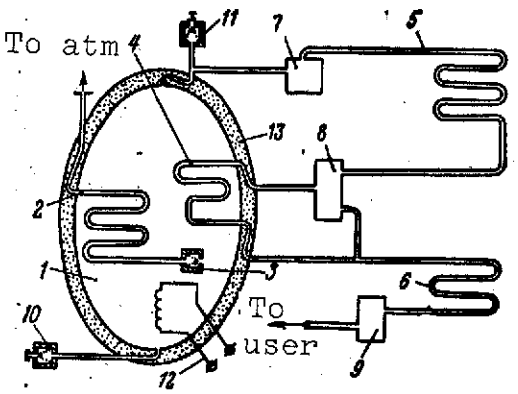


Figure 4.38. Possible oxygen storage scheme.

1 — Dewar; 2 — heat exchanger coil; 3 — excess internal pressure dump valve; 4 — inner heat exchanger; 5, 6 — outer heat exchangers; 7 — electrically controlled starting valve [electrovalve]; 8 — bypass valve; 9 — pressure regulator; 10 — filler; 11 — safety valve; 12 — electric heater; 13 — thermal insulation layer.

At supercritical pressure, oxygen is a liquid if its temperature is below the critical value, or a gas if it is above the critical value. The systems for storing and feeding oxygen at supercritical pressure are quite simple in construction, operationally reliable, and have high specific volumetric parameters. However, the comparatively high working pressure used in this case leads to increase of vessel weight. /125

A possible system for storing oxygen at supercritical pressure is shown in Figure 4.38.

The pressure in the vessel 1 increases in the absence of oxygen flow because of unavoidable heat flux from the outside. When the pressure reaches a definite value, the valve 3 opens. The oxygen discharging through this valve is throttled, cooled, removes heat from the liquid oxygen located in the vessel 1 as it flows through the heat exchanger coil 2, and is then discharged to the atmosphere.

Oxygen supply to the users takes place when the electrically operated valve 7 is opened. The oxygen is warmed in the heat exchanger 5 and then flows to the bypass valve 8. In this valve, part of the oxygen flow is directed to the heat exchanger 4 to warm the liquid oxygen in the vessel 1 and maintain constant pressure therein, the remainder enters the heat exchanger 6, where the oxygen is heated to normal temperature.

TABLE 4.21*

SPECIFIC WEIGHT AND SPECIFIC HEAT OF LIQUID OXYGEN AT VARIOUS TEMPERATURES AND PRESSURES [21]

Temperature ° C	Pressure, kG/cm²					
	5	20	40	50	60	80
—185	1,138 0,415	1,150 0,406	1,175 0,396	1,187 0,392	1,198 0,387	1,221 0,383
—160	—	1,028 0,440	1,058 0,427	1,073 0,421	1,088 0,416	1,118 0,410
—140	—	—	0,924 0,490	0,945 0,474	0,966 0,462	1,003 0,442
—120	—	—	0,717 0,498	0,773 0,695	0,814 0,630	0,888 0,527
—	—	—	—	0,636 0,922	0,728 0,830	0,836 0,593

Note: Numerator is sp.wt. γ in G/cm³; denominator is sp.heat cp in kcal/kG/°C.

*Commas in the numbers indicate decimal points.

The regulator 9 automatically maintains the required oxygen pressure in the lines leading to the user. After activation of the electrically operated valve 7, the pressure in the vessel 1 decreases to the working pressure and the valve 3 closes. Constant working pressure in the supply system is automatically maintained thereafter by the valve 8.

Data on the specific weight and specific heat of liquid oxygen at various temperatures and pressures [21] are presented in Table 4.21. /126

Equipment for Drying Air

In the course of time, the air in the pressure suit saturates with the moisture released by the wearer as a result of breathing and perspiring. Forced circulation of the air does not aid in evaporating the moisture and removing it from the suit; therefore, drying of the air in the pressure suit LSS is accomplished with the aid of regenerable and nonregenerable absorbers by condensing the moisture and collecting it in a special moisture collector.

Various sorbents may be used as regenerable absorbers: zeolites, silica gels, alumo gels, and other chemical substances.

The absorbing capacity of some zeolites was presented above (see Table 4.15).

Drying of the air by mineral sorbents is based primarily on the phenomenon of adsorption and subsequent capillary condensation of the moisture in the branched porous structure of the dessicant. Such drying agents include silica gel, alumo gel, and others.

Silica gel (SiO_2) is the product of dehydration of silicic acid gel, obtained as a result of the action of sulfuric or hydrochloric acid or solutions of various salts on a sodium silicate (dissoluble glass) solution.

Alumo gel or activated aluminum consists basically of aluminum oxide Al_2O_3 in the form of small white cylinders or spherules.

The ability of silica gel to absorb water vapor decreases with temperature increase and reduction of the water vapor partial pressure.

In the course of water vapor absorption by silica gel, heat is released, consisting of the heat of wetting (110 kcal/kG) and the heat of condensation (600 kcal/kG) of the adsorbed moisture. /127

We differentiate microporous (with pore radius about 15 Å) and macroporous (with pore radius more than 50 Å) silica gel. Microporous silica gel is used to absorb water vapor from air with low moisture content.

The basic characteristics of silica gel are shown in Tables 4.22 and 4.23.

In designing the silica gel filter-dryer, the unknowns are primarily its volume, absorber layer thickness h, and area S

$$V = hS = \frac{G_{ma}(d_i - d_f)\tau}{\gamma_s u_{max}}, \qquad (4.44)$$

where h is the absorber layer thickness in m; S — cross section area of this layer in m^2; G_{ma} — moist air flowrate in kG/h; d_i and d_f — respectively, the initial (at filter entrance) and final (at filter exit) moisture content of the air in kG/kG of dry air; τ — absorber operating time in hours; γ_s — silica gel gravimetric (bulk) specific weight in kG/m^3; u_{max} — silica gel maximum moisture content (on the average u_{max} = 0.08 — 0.1 kG moisture/kG gel).

TABLE 4.22*

CHARACTERISTICS OF MICROPOROUS LUMP SILICA GEL [10]

Characteristic	Designation			
	KSM	ShSM	MSM	ASM
Grain size, mm	2,7—7	1,5—3,5	0,25—2	0,20—0,5
Bulk weight in terms of dry substance in g/liter (no less than)	670	670	670	670
Moisture capacity in terms of water vapor at 20° C and relative humidity in %				
20 no less than	9,5	9,5	9,0	9,0
40 no less than	20,0	20,0	20,0	19,0
60 no less than	29,0	29,0	29,0	28,0
100 no less than	35	35	35	35
Drying losses at 150° C in % (no more than)	10	10	10	10

*Commas in the numbers indicate decimal points.

TABLE 4.23*

CHARACTERISTICS OF MACROPOROUS LUMP SILICA GEL [10]

Characteristic	Designation			
	KSM	ShSM	MSM	ASM
Grain size, mm	2,7—7	1,5—3,5	0,25—2	0,2—0,5
Bulk weight in terms of dry substance in g/liter (no less than)	400—500	400—500	400—500	400—500
Moisture capacity in terms of water vapor at 20° C and relative humidity no more than 100%	70	70	70	70
Drying losses at 150° C in % (no more than)	5	5	5	5

*Commas in the numbers indicate decimal points.

The absorber layer area (canister section) S is usually determined from the condition

$$S = \frac{G_{ma}(1 + d_i)}{\gamma_{ma} 3600 v_a} \tag{4.45}$$

where γ_{ma} is the specific weight of the moisture air at the filter inlet in kG/m^3; v_a — inlet air velocity in m/s.

From the last two equations, we obtain

$$h = 3600 \frac{(d_i - d_f)\, \gamma_{ma} \tau v_a}{(1 + d_i) U_{max} \gamma_s} \tag{4.46}$$

The recommended values are v_a = 0.15 — 0.5 m/s.

The head losses because of resistance of a filter with silical gel having grains of diameter 1 — 3 mm at air temperature 20° C are

$$\Delta p = (470—535)\ h v_{ma} \tag{4.47}$$

where v_{ma} is taken in the range 0.15 — 0.5 m/s.

The adsorption capability of alumo gel is lower than that of silica gel, but the degree of air drying by alumo gel is higher. Alumo gel is used at temperatures up to 25° C.

The construction of an air filter-dryer using substances which absorb moisture is shown in Figure 4.39. As such a substance we can use polyvinyl formal foam (PVFF), which is a foamed product of condensation of polyvinyl alcohol and formal, rigid in the dry state and elastic when moistened. Three grades of polyvinyl formal foam as a function of density are produced:

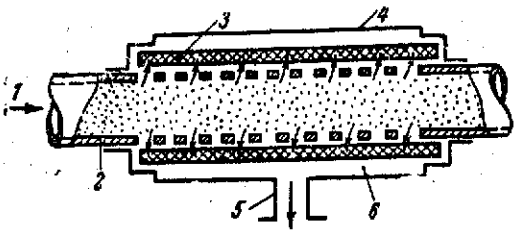


Figure 4.39. Air dryer (water separator) based on condensing water vapor from the air.

1 — air containing water vapor; 2 — perforated tube; 3 — wick which absorbs moisture droplets; 4 — moisture collector case; 5 — liquid outlet fitting; 6 — low air pressure cavity.

TPVF-1, TPVF-2, and MPVF.

The basic characteristics of polyvinyl formal foam are presented in Table 4.24.

After complete saturation, the ability of PVFF to absorb moisture can be restored by mechanical squeezing of the moisture from the PVFF, after which it can be reused.

TABLE 4.24*

BASIC CHARACTERISTICS OF POLYVINYL FORMAL FOAM AS AN AIR DRYER (TUV 86-67)

Characteristic	Designation		
	MPVF	TPVF-1	TPVF-2
Sp. wt, G/cm^3	0,1—0,23	no more than 0,13	0,1—0,23
Mositure absorption in 2 hours in % (no less than)	—	700	700
Residual moisture content in % (no more than)	8,0	8,0	8,0

*Commas in the numbers indicate decimal points.

A technique for drying air by condensing the moisture from the air and collecting the condensation in a special collector is shown in Figure 3.19.

The construction of such a dryer is shown in Figure 4.39. As a result of the pressure difference in the tube 2 and the

cavity 6, the moisture droplets suspended in the air are absorbed by the wick 3 and are directed from the fitting 5 along a tube to the moisture collector. The moisture collector is a cylindrical vessel with the membrane 1 separating it into two parts (Figure 4.40). The vessel space above the membrane communicates with the air dryer while the space below the membrane is the vessel for storing the water supply.

As the water supply is expended, its level drops and the space above the membrane is filled with water coming from the dryer.

Heat Exchangers

The heat exchangers in pressure suit LSS cool the air in the suit ventilating system and the water circulating in the liquid cooled garment (LCG).

Experience in using these heat exchangers has shown that they must:

— cool the air from 25 to 5° C with flowrate up to 300 liters/minute and differential pressure in the range from 0.2 to 0.4 kG/cm^2;

— cool the water or other coolant from 20 to 7° C with flowrate from 1 to 3 liters/minute.

Heat exchanger calculations usually amount to determining the required heat transfer surface area on the basis of the properties of the selected coolant, heat flux, coolant temperature at the inlet to and exit from the heat exhcnager, and also the total hydraulic resistance of the heat exchanger for the given coolant pressure therein.

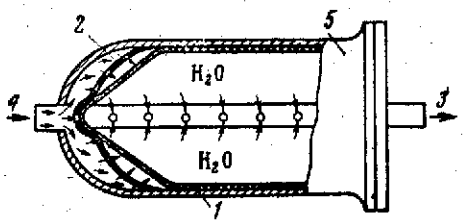


Figure 4.40. Air dryer moisture collector.

1 — elastic membrane; 2 — space above membrane; 3 — water flow to heat exchanger; 4 — water from dryer; 5 — moisture collector case.

We have noted previously that the total hydraulic resistance of the heat exchanger includes:

— the coolant head losses at the exchanger entrance;

— the internal hydraulic resistance of the heat exchanger owing to friction, local resistances, and heat transfer intensity, determined by special methods for calculating internal hydrogasdynamics;

— the coolant head losses as the coolant stream expands at the exit from the heat exchanger.

The effectiveness of a heat exchanger is usually evaluated on the basis of its weight coefficient E = Q/G (ratio of the amount of heat transferred to the coolant per unit time in kcal/h to heat exchanger weight in kG).

Evaporative and sublimative heat exchangers are usually used in pressure suit LSS.

The evaporative heat exchangers used to cool air are based on utilization of the latent heat of vaporization of liquids.

As is well known, boiling of a heated liquid takes place /130
if the temperature of its surface layer is higher than the saturated vapor temperature of the liquid at the given pressure.

The amount of heat transferred by the heat exchanger wall to the boiling liquid is:

$$Q = \alpha_c(t_w - t_o)S\tau, \qquad (4.48)$$

where α_c is the coefficient of convective heat transfer, S — heating area, τ — time.

The amount of heat removed by the evaporative heat exchanger is determined by the pressure at which coolant boiling takes place for the given temperature, the temperature head (differential), the condition of the heating surface, and the physical properties of the liquid (coolant) and its saturated vapor.

The effectiveness of the evaporative heat exchanger is also characterized by the amount of evaporating liquid which is carried away with the vapor for different thermal loadings. It usually amounts to 8 — 15% of the total amount of coolant in the heat exchanger.

The coolants for evaporative heat exchangers are usually liquids with high latent heat of vaporization which are harmless to man and safe with respect to fire. Such liquids include water, water-alcohol and water-glycol mixtures.

The basic thermophysical characteristics of some coolants are presented in Tables 4.25 and 4.26.

One possible dual-loop evaporative heat exchanger is shown in Figure 4.41. In this heat exchanger, the coolant boiling temperature must be below the temperature of the circulating water. The coolant vapor pressure ahead of the valve 3 must be higher than the atmospheric air pressure, otherwise vapor will escape from the evaporator and boiling of the coolant at the given temperature will become impossible.

TABLE 4.25**

WATER BOILING TEMPERATURE AT VARIOUS PRESSURES*

Pressure mm Hg	Boiling point ° C	Pressure mm Hg	Boiling point ° C	Pressure mm Hg	Boiling point ° C	Pressure mm Hg	Boiling point ° C
760	100	—	—	92,5	50	6,1	4
525	90	—	—	55,3	40	4,58	0
355	80	17,5	20	42,17	35	3,28	—4
233,7	70	12,78	15	31,82	30	2	—10
149,4	60	9,2	10	23,75	25	1,3	—16
				—	—	0,78	—20

*Karyakin, N. I., et al. Physics Handbook, Vysshaya Shkola, Moscow, 1962.

**Commas in the numbers indicate decimal points.

Water, whose boiling point is also higher than that of the coolant being evaporated, flows in the second loop 4. The valve 3 maintains the specified differential pressure in the heat exchanger. The heat exchanger evaporator is filled with some sort of porous material (for example, polyvinyl formaldehyde foam) and is saturated with the liquid coolant (water). The /131
necessity for a porous evaporator is due to the fact that, under weightlessness, there is not clear separation of the phases (liquid, vapor) and the coolant (water) present in the heat exchanger will flow to the outside through the valve 3.

The heat exchangers of the evaporative type have the following drawbacks associated with the principle of their operation:

— losses of the liquid coolant (water), which is carried away from the heat exchanger to the atmosphere together with its vapor;

TABLE 4.26*

BASIC PHYSICAL CHARACTERISTICS OF SOME COOLANTS (HEAT CARRIERS)

Coolant	Chemical formula	Molecular wt, g	Boiling point (at 760 mm Hg), °C	Critical point parameters			Freezing point, °C	Adiabatic exponent
				Temperature °C	Pressure kG/cm²	Sp. vol., m³/kG		
Ammonia	NH_3	17,03	—33,4	132,4	115,2	4,13	—77,7	1,3
Carbon dioxide	CO_2	44,01	—78,5	31,0	75,2	2,16	—56,6	1,3
Freon-11	$CFCl_3$	137,39	23,7	198,0	44,6	1,805	—111,0	1,13
Freon-12	CF_2Cl_2	120,92	—29,8	112,0	41,96	1,793	—155,0	1,14
Freon-13	CF_3Cl	104,47	—81,5	28,78	39,36	1,721	—180,0	—
Freon-21	$CHFCl_2$	102,92	8,90	178,5	52,68	1,915	—135,0	1,16
Freon-22	CHF_2Cl	86,48	—40,8	96,0	50,33	1,905	—160,0	1,20
Freon-114	$C_2F_4Cl_2$	170,91	3,5	145,8	33,4	1,715	— 94,0	1,107
Freon-142	$C_2H_3F_2Cl$	100,48	—9,25	137,0	42,0	2,30	—130,8	1,135

*Commas in the numbers indicate decimal points.

— necessity for using a special device to ensure the required proportioned coolant input to compensate for its leakage into the atmosphere;

— the coolant temperature in the evaporator must be above freezing;

— possible icing up of the valve through which the coolant vapor is discharged to the atmosphere.

The sublimative heat exchangers are based on utilization of the latent heat of sublimation during vaporization of solids. This heat includes the latent heats of vaporization and freezing. For example, for water, it is made up of the latent heat of its vaporization at 0° C (about 600 kcal/kG) and the

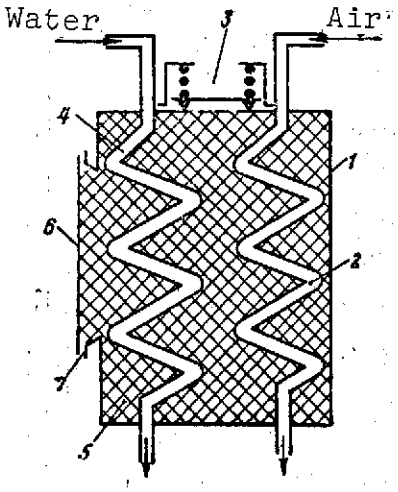


Figure 4.41. Schematic of two-loop evaporative heat exchanger.

1 — sealed case; 2 — air cooling loop; 3 — pressure valve; 4 — water cooling loop; 5 — porous evaporator saturated with coolant; 6 — cover; 7 — throat for coolant filling.

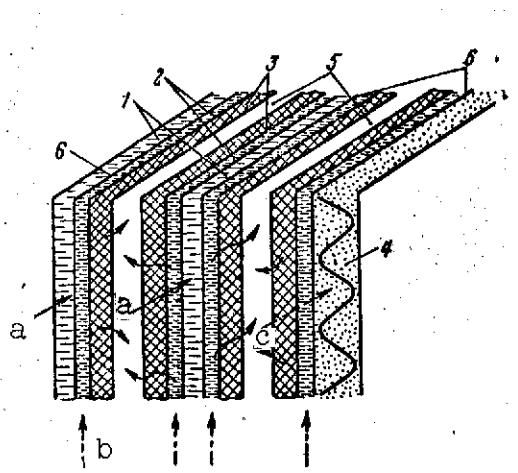


Figure 4.42. Schematic of two-loop sublimative heat exchanger.

1 — liquid coolant (cooled water); 2 — sublimable water; 3 — porous plates; 4 — channels for gaseous coolant; 5 — vacuum channels; 6 — separators; A — liquid coolant 1 flow; B — sublimable water 2 flow; C — gaseous coolant flow.

latent heat of freezing (about 80 kcal/kG). Therefore, minimum expenditure of the substance being evaporated (coolant) is achieved with sublimation.

The sublimative heat exchanger principle of operation is clarified in Figure 4.42. It involves sublimation of the ice which forms in the plate capillaries. The liquid coolant (water being cooled) stream 1 flows through the slotted heat exchanger channels as shown by the arrows A and gives up its heat through the walls 6, made from material with good thermal /132 conductivity, to the water being sublimated 2. Sublimation of the water takes place in the plates 3, whose pores communicate with the channels 5. The water vapor formed during sublimation enters the channels 5 and is then discharged to the surroundings.

The sublimated water is replaced by automatically regulated water flow from a supply container. The sublimated water consumption rate is

$$G_{wat} = \frac{Q_{\Sigma}}{r_{vap} + r_{fr}} \qquad (4.49)$$

where Q_{Σ} is the total amount of heat removed, r_{vap} and r_{fr} are, respectively, the latent heats of the vaporization and freezing of water at the given pressure.

Formula (4.50) does not take into account the heat expenditure in changing the temperature of the sublimable water entering the heat exchanger, which, in view of its insignificance, can be neglected.

The primary elements of the sublimative heat exchanger are the porous vaporizers in which the sublimation process takes place. It is believed that the powder metallurgy methods will permit obtaining porous materials from any of the metals.

The most important characteristics of porous vaporizers are the volumetric porosity, defined as the ratio of the total pore volume to the entire volume of the element, and the surface porosity, defined by the ratio of the total pore cross section area to the element area.

Liquid coolant evaporation rate as a function of average evaporator pore diameter is shown in Figure 4.43 [13].

The characteristics of the porous vaporizers fabricated from aluminum are:

volumetric porosity	15 — 30%
average pore dimension	4 — 20 microns
plate thickness	2 — 3 mm
thermal conductivity	9.46 — 21.5 kcal/m/h/°C = 11 — 25 W/m/°K

/133

The characteristics of the porous vaporizers made from titanium are [13]:

volumetric porosity	20 — 40%
average pore dimension	3 — 20 microns
plate thickness	1 — 6 mm
thermal conductivity	1.72 — 4.3 kcal/m/h/°C = 2 — 5 W/m/°K

The water flow in the evaporator pore capillaries takes place under the influence of pressure and surface tension forces. Moreover, because of the abrupt pressure reduction in the channels 5 (see Figure 4.42), the water boils in the capillaries, evaporates, and is cooled. Depending on the ambient conditions, the water freezes either in the depth of the capillaries or at the exit from them. In the latter case, the water is usually discharged into the surrounding space. After freezing of the water, the sublimation process itself begins — ordered evaporation of the ice.

The process of freezing of the water and vaporization of the ice in the microcapillaries of the vaporizer porous plates takes place with minimum nonproductive coolant expenditure.

At the critical pressure p_{cr}, air will break through the micropores which have previously been filled with water. This pressure characterizes the magnitude of the surface tension forces in the capillaries.

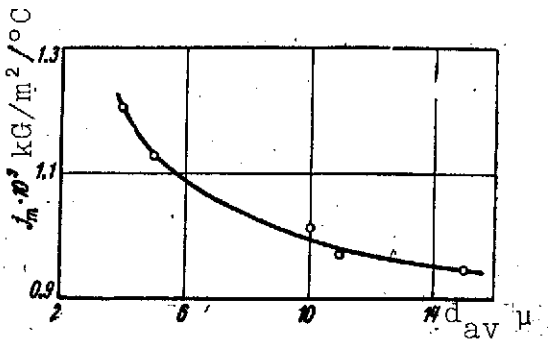


Figure 4.43. Evaporation rate (j_m) of liquid coolant in porous evaporator versus average pore diameter (d_{av}) [13].

Calculations show that the capillary pore diameter changes most sharply with pressure change to a critical value of 1 kG/cm^2. Thus, while the maximum pore diameter for p_{cr} = 0.1 kG/cm^2 is 30 μ, for p_{cr} = 1 kG/cm^2 it decreases correspondingly to 3 μ.

In the evaporation zone, a pressure arises which is determined by the abrupt increase of the specific volume of the evaporating substance and by the hydraulic resistance of the pore channels.

Upon exceeding some definite magnitude of the heat flux, sublimation of the ice becomes impossible and the water begins to filter through the material pores into the evacuated heat exchanger channels. The magnitude of this critical flux depends on the material porosity, pore diameter, and the water pressure (the higher the porosity, the smaller the pore diameter, and the lower the water pressure, the greater is the magnitude of the critical heat flux).

With increase of the heat flux, the sublimation zone approaches the surface adjacent to the evacuated medium.

The specific cooling capacity of the porous plates (per unit surface area) reaches $(1.29 — 1.72)\cdot10^4$ kcal/h/m^2 = $(1.5 — 2)\cdot10^4$ W/m^2.

Depending on the temperature and presence of air bubbles, /134 the specific weight of ice is taken equal to be 0.917 kG/liter in practical calculations (when water changes to ice its volume increases by about 9%). In calculations, we should also consider that with pressure increase, the melting point of ice decreases (at normal pressure it is 0° C). The latent heat of melting of ice is 80 kcal/kG to within accuracy adequate for practical calculations. At temperatures from 0 to -20° C, the average specific heat of ice is 0.5 kcal/kG/°C.

The thermal conductivity of ice as a function of its temperature is

t °C	0	—50	—100
λ kcal/m/h/°C	1.92	2.39	2.99

The resistance of ice to compression σ_{ice} as a function of temperature is [14]:

t°C	0	—10	—20
σ_{ice} kG/cm^2	15	30	50

Sublimative heat exchangers have several advantages in comparison with the evaporative type, since during vaporization of the solid coolant, phase separation usually takes place more stably and sharply than during vaporization of a liquid coolant. This characteristic is important under conditions of reduced gravitation and weightlessness. Moreover, the phase change during sublimation takes place at lower temperatures.

Injectors

The operating principle of the injector (ejector) is based on using the kinetic energy of a compressed gas or vapor injecting stream discharging from a nozzle to entrain (pump) another injected gas or liquid (Figure 4.44). A constant pressure (2 — 8 kG/cm^2) is usually maintained ahead of the injector.

In the pressure suit LSS injectors are used to circulate gases in the ventilation systems.

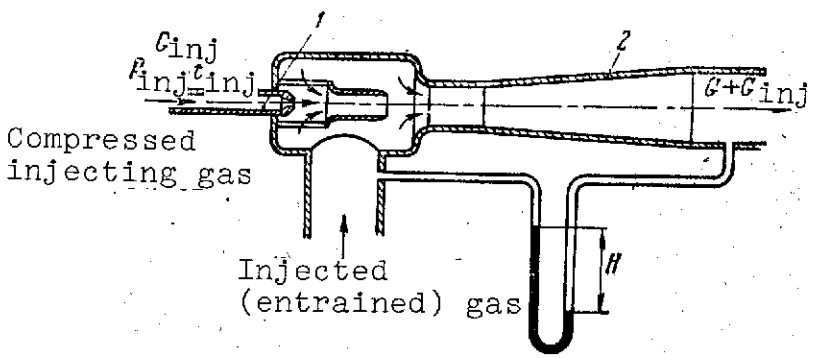


Figure 4.44. Injector for circulating air in pressure suit system.

1 — primary nozzle; 2 — diffuser.

In the injector, the injecting gas stream flows through a nozzle or series of nozzles in which air entrainment takes place and enters the diffuser, where its velocity head is converted into static pressure [16]. The higher the head which the injector must create, the smaller will be the amount of air entrained by the injector. Injector effectiveness is characterized by the *injection coefficient* /135

$$q_G = \frac{G_{ent}}{G_{inj}}, \qquad (4.50)$$

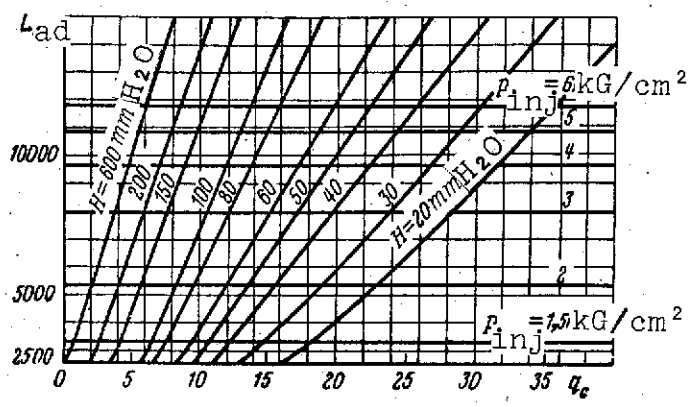


Figure 4.45. Graph for determining injection coefficient q_G appearing in (4.52).

where G_{ent} and G_{inj} are, respectively, the weights of the entrained and injecting gas.

The basic data for determining the injector dimensions are the entrained air weight flowrate G_{ent} in kG/sec, or the volumetric weight W_{ent} in m^3/sec, and the head H at which the entrained air enters the system in mm H_2O).

By the injector head H, we mean the difference between the pressure in the injector inlet line and the pressure in the injector delivery line downstream of the diffuser. If the flow velocity at the injector inlet and exit exceeds 5 m/sec, the velocity head must be added to the head H.

For given initial values (G_{ent}, H_{ent}, W_{ent}), the injector dimensions are determined as follows:

1. The work of adiabatic expansion of the injecting gas is

$$L_{ad}=\frac{k}{k-1}RT_{inj}\left[1-\left(\frac{p_{cas}}{p_{inj}}\right)^{\frac{k-1}{k}}\right]\text{kG/m}, \qquad (4.51)$$

where k is the adiabatic exponent; p_{inj} and T_{inj} — absolute pressure and temperature of the compressed injecting gas, p_{cas} — absolute pressure in the injector case, R — gas constant of the injecting gas.

2. From the found value of L_{ad} and the given injector head H, we determine, with the aid of Figure 4.45, the injection coefficient q_G.

The graph is plotted from test results of injectors [16] with entrained air p = 760 mm Hg and t_{ent} = 15° C, with injecting gas (air) p_{inj} = 1.5 — 6 kG/cm² and t_{inj} = 15° C.

If the absolute pressure and the temperature of the entrained air do not correspond to the assumed values, a correction must be made to the value of the injection coefficient q_G obtained from Figure 4.45. For these cases, the new injection coefficient $q_G = q_G\sqrt{\gamma/\gamma_0}$, where q_G is the injection coefficient found from Figure 4.45, γ — specific weight of the entrained air under conditions differing from the conditions for Figure 4.45, γ_0 — specific weight of the entrained air at 760 mm Hg and 15° C (γ_0 = 1.225 kG/m³). /136

Substituting the value of γ_0, we obtain

$$q_0=0{,}9\,q_G\sqrt{\gamma}. \qquad (4.52)$$

3. For the specified entrained air flowrate G_{ent} and the found coefficient q_G, we determine from (4.51) the injecting gas flowrate

$$G_{inj} = G_{ent}/q'_G.$$

4. The volumetric flowrate of the gas mixture through the injector diffuser inlet throat is (Figure 4.46)

$$W_E = W_{ent} + W_{inj},$$

where W_{ent} is the entrained gas volume at the specified pressure and temperature, W_{inj} is the injecting gas volume upon expansion to the pressure p_{cas} in the injector case and at the mixture temperature T in the case.

$$W_{ent} = G_{ent}\gamma_1 \ m^3/sec; \ W_{inj} = \frac{RT}{p_1 \cdot 10^4} G_{inj}.$$

5. The average injecting gas velocity in the diffuser inlet throat on the basis of the specified injector static head H is

$$v_m = \sqrt{\frac{2H}{\varrho_1 \varphi_{inj}}} \ m/s$$

where ϱ_1 is the mass density of the gas at the pressure and temperature in the injector chamber in $kG/sec^2/m^4$, φ_{inj} — coefficient of velocity head utilization (can be taken approximately as $\varphi_{inj} = 0.8$).

6. The area of injector diffuser inlet section on the basis of the volumetric flowrate W_E and velocity v_m is

$$S_m = W_E/v_m \ м^2.$$

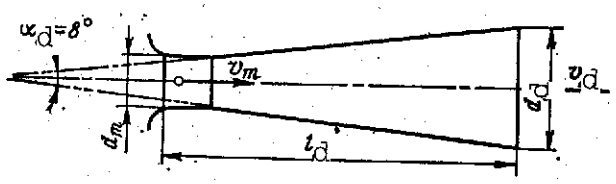


Figure 4.46. Basic parameters of injector diffuser.

From the found area S_m we determine the diffuser inlet throat diameter d_m and the diffuser exit section diameter d_d for the specified exit velocity v_d = 5 — 10 m/sec.

The diffuser length for the usual diffuser divergence angle d_d = 5° — 8° (see Figure 4.46) is

$$l_d = \frac{d_d - d_m}{2 \operatorname{tg} \frac{\alpha_d}{2}}. \qquad (4.53)$$

After determining the diffuser dimensions, we can refine /137
the value of the coefficient φ_{inj} (as a fraction of the velocity head $\rho v_m^2/2$):

(a) the friction losses in the diffuser

$$\xi_{fr} = \frac{c_f}{\sin \alpha_d/2} \left(\frac{m^2 - 1}{m^2}\right),$$

where c_f = 0.002 is the friction coefficient, $m = S_d/S_m$ is the ratio of the diffuser exit and inlet section areas, α_d is the diffuser divergence angle;

(b) the expansion losses

$$\xi_{exp} = \sin \alpha_d \left(\frac{m-1}{m}\right)^2;$$

(c) the outlet losses $\xi_{out} = 1/m^2$.

With account for these losses, the velocity head utilization coefficient is

$$\varphi_{inj} = 1 - (\xi_{fr} + \xi_{exp} + \xi_{out}).$$

REFERENCES

1. Problemy kosmicheskoy biologii (Problems of Space Biology), edited by Academician V. N. Chernigorskiy, Vol. 11, Nauka, Moscow, 1969.

2. Idel'chik, I. Ye. Spravochnik po gidravlicheskim soprotivleniyam (Handbook on Hydraulic Resistance). Gosenergoizdat, Moscow, 1960.

3. Bashta, T. M. Gidravlicheskiye privody letatel'nykh apparatov (Flight Vehicle Hydraulic Drives), Mashinostroyeniye, Moscow, 1967.

4. Kiselev, P. G. Spravochnik po gidravlicheskim raschetam (Handbook on Hydraulic Calculations), Gosenergoizdat, Moscow, 1961.

5. Bashta, T. M. Mashinostroitel'naya gidravlika (Mechanical Hydraulics), Mashgiz, Moscow, 1963.

6. Orlov, V. A. Malogabaritnyye istochniki toka (Miniature Current Sources), Voyenizdat, Moscow, 1965.

7. Romanov, V. V. and Yu. M. Khashev. Khimicheskiye istochniki toka (Chemical Current Sources), Sovetskoye Radio, Moscow, 1968.

8. Serpionova, Ye. N. Promyshlennaya adsorbtsiya gazov i parov (Industrial Adsorption of Gases and Vapors), Goskhimizdat, Moscow, 1956.

9. Dubinin, M. M. Sinteticheskiye tseolity (Synthetic Zeolites), Izdatel'stvo AN SSSR, Moscow, 1962.

10. (Handbook on Space Biology and Medicine), edited by A. I. Burnazyana et al., Meditsina, Moscow, 1967.

11. Kalinushkin, M. M. Ventilyatornyye ustanovki (Fan Systems), Vysshaya shkola, Moscow, 1967.

12. Chuprakov, Yu. P. Osnovy gidro- i pnevmoprivodov (Fundamentals of Hydraulic and Pneumatic Drives), Mashinostroyeniye, Moscow, 1966.

13. Selivanov, V. V. and V. N. Shmigora, "Study of the Process of Liquid Evaporation from Porous Metal under Vacuum Conditions," Inzhenerno-fizicheskiy zhurnal, Vol. 14, No. 1, 1968.

14. Komarov, N. S. Kholod (Cold), Press of the Ministry of Light and Foodstuffs Industry, Moscow, 1953.

15. Bykov, L. T., M. S. Yegorov, and P. V. Tarasov. Vysotnoye oborudovaniye samoletov (Aircraft Altitude Equipment), Oborongiz, Moscow, 1958.

16. Rzhanitsyn, N. A. Vodostruynyye nasosy (gidroelevatory) [Waterjet Pumps (Hydroelevators)], State Joint Scientific and Technical Publishing House of the People's Commissariat of Heavy Industry of the USSR, 1938.

17. Spravochnik khimika (Chemistry Handbook), Vol. 1, Khimizdat, Moscow, 1951.

18. Stepanov, A. A. Tsentrobezhnyye i osevyye nasosy (Centrifugal and Axial Pumps), Mashgiz, Moscow, 1960.

19. Karyakin, N. I., et al. Kratkiy spravochnik po fizike (Physics Handbook), Vysshaya shkola, Moscow, 1962.

20. Kochetkov, N. D. Kholodil'naya tekhnika (Refrigeration Engineering), Mashinostroyeniye, Moscow, 1966.

21. Chirkin, V. S. Teplofizicheskiye svoystva materialov (Thermophysical Properties of Materials), Fizmatgiz, Moscow, 1959.

22. Mikheyev, M. A. Osnovy teploperedachi (Fundamentals of Heat Transfer), State Scientific and Technical Power Engineering Publishing House, Moscow, 1956.

23. Knyazev, V. N. Osnovnyye voprosy kislorodnogo obespecheniya vysotnykh poletov (Basic Problems of Oxygen Supply for High Altitude Flights), Voyenizdat, Moscow, 1947.

24. Men'shov, A. I. Kosmicheskaya energonomika (Space Energonomics), Nauka Press, Moscow, 1971.

CHAPTER 5
EMERGENCY-SURVIVAL PRESSURE SUIT CONSTRUCTION

1. Purpose and Requirements /138

The emergency-survival pressure suit is an individual suit for flight vehicle crewmembers which is used by them in the following cases:

— sudden loss of cabin pressurization;

— disruption of the required gas composition of the air in the cabin and excessive cabin temperature increase or decrease;

— bailout from a flight vehicle in an emergency situation.

The suit construction must be compatible with the life support system for the individual in the suit.

The individual's stay time in the pressure suit depends on the systems which provide his food and support his natural functions. According to the published data, this time is:

— 12 — 15 days for the pressurized cabin equipped with a system for collection of liquid and solid wastes;

— 2 — 3 days for the depressurized cabin equipped with drinking water supply and liquid waste collection systems.

Depending on the type of spacecraft (SC) in which they are used, the emergency-survival pressure suits can be subdivided into *aircraft* and *space* types.

High altitude (aircraft) emergency-survival pressure suits are used aboard airplanes, space suits are used aboard satellite spacecraft, orbital space stations (OSS), and interplanetary spacecraft.

The basic elements of the pressure suit are the shell and the helmet.

The pressure suit assembly includes the cosmonaut's outer garment, undergarment, thermal protection garment (TPG), footwear, communications equipment and survival gear.

The vitally important functions performed by the pressure suit have led to the necessity for establishing stringent requirements on the suit. In each particular case, these requirements may be supplemented and altered as a function of spacecraft construction and flight objectives.

Soviet and foreign experience makes it possible to present typical general requirements which are considered in pressure suit development.

General Requirements on Emergency-Survival Pressure Suits

1. Least possible restriction of individual mobility when aboard the craft and outside the craft.

2. High operational reliability.

3. Lowest possible weight and size.

4. Simplicity and convenience of use and servicing, repairability (possibility of repair and replacement of individual elements during operation).

5. Safety with regard to fire. /139

6. Highest possible "survivability" in case of mechanical damage.

7. High resistance to vibration and thermal stability in the specified temperature ranges.

8. Strength margin:

— threefold in relation to the working static load;

— twofold in relation to the dynamic load (verified in a differential barochamber).

9. Possibility of manual regulation of pressure in suit, amount and temperature of the air supplied for ventilation.

10. Limitation of the contaminant content in the inhaled air in accordance with the data presented in Table 4.1.

11. Possibility of donning and removing suit without outside help.

2. Pressure Suit Shell

The pressure suit shell must be hermetic in order to maintain the internal differential pressure and sufficiently flexible for the individual to perform the specified complex of movements.

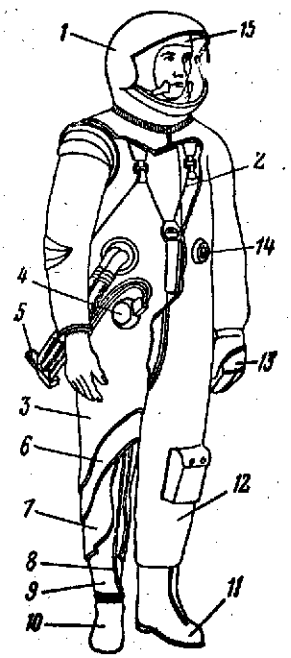


Figure 5.1. Typical emergency survival pressure suit with multilayer shell.

1 — helmet; 2 — restraint system; 3 — restraint layer; 4 — hermetic communications connector; 5 — single-point connector for life support system hoses; 6 — shell hermetic layer; 7 — shell underlayer; 8 — ventilation system tube; 9 — underwear; 10 — socks; 11 — removable footwear; 12 — outer garment; 13 — removable gloves; 14 — pressure regulator; 15 — communications helmet.

The multilayer shell consists of several shells (layers); restraint, hermetic, and lining, the restraint system, and disconnects for the helmet and gloves (Figure 5.2).

An opening which can be sealed by a special appendix (Figure 5.3) is provided in the shell for donning the pressure suit. In some suits, the opening is closed by a hermetic zipper in place of the appendix.

The restraint layer takes the tensile loads which arise as a result of internal differential pressure.

The fabric used in this layer must have the specified strength under biaxial loading in the warp and woof directions and high resistance to tearing.

Figure 5.4 shows various typical seams for joining fabrics. The selection of a particular seam type is made with account for the nature of the loading and the constructional characteristics of the joint. Thus, for high tensile forces, a "lock" seam is used, and the number of stitch rows depends on fabric strength

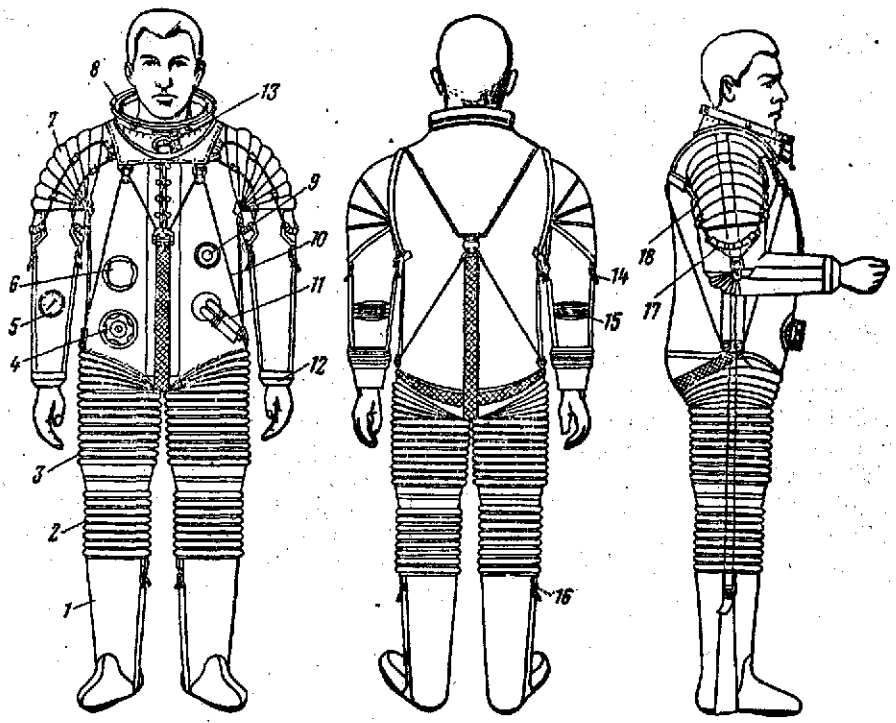


Figure 5.2. Shell of emergency survival pressure suit.
1 — restraint layer; 2 — knee hinge; 3 — hip hinge; 4 — suit pressure regulator; 5 — suit pressure gage; 6 — hermetic communications connector; 7 — shoulder hinge; 8 — neck ring; 9 — safety valve; 10 — tensioning system cable; 11 — air inlet hose; 12 — cuff; 13 — liquid food intake valve; 14 — buckle for regulating sleeve length; 15 — elbow hinge; 16 — buckle for regulating trouser length; 17 — shoulder hinge guides; 18 — shoulder hinge tensioning cable.

and the loads which develop in the fabric. It is recommended that each of the seams planned for use be subjected to preliminary testing on specially prepared specimens.

The netting shown in Figure 5.5, fabricated from strong synthetic threads (dacron, for example), can be used as the restraint layer. It is convenient in operation, the longitudinal loads in the netting are taken by straps located along the torso and limbs. Pressure suit mobility is reduced when using the netting type restraint layer.

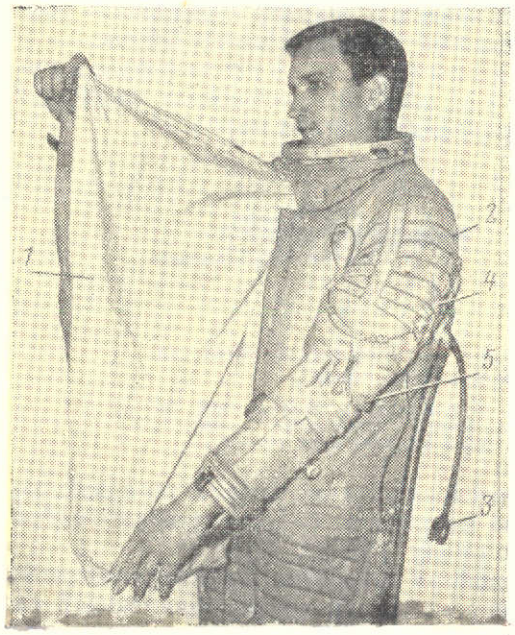


Figure 5.3. Opening and appendix in emergency survival pressure suit [2].

1 — appendix; 2 — restraint strap which takes axial forces; 3 — hermetic communications connector; 4 — shoulder hinge guide sleeves; 5 — elbow hinge with structural elements in "orange peel" form.

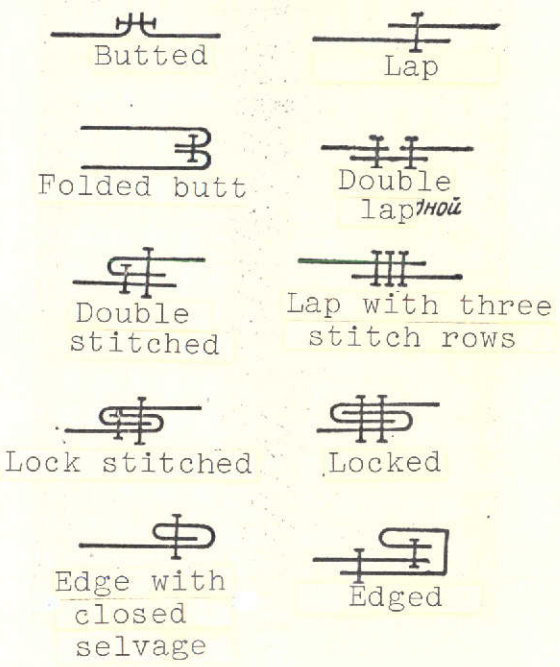


Figure 5.4. Typical seams for pressure suit shell fabrics.

The hermetic layer is made of sheet rubber or rubberized fabric.

In spite of the fact that the materials from which the hermetic layer is fabricated are highly impermeable to air, the pressure suit shell does not maintain hermeticity in practice, primarily because of the large number of separable joints in it.

With 0.2 kG/cm^2 differential pressure and conventional fabrication technology, the air leakage from the pressure suit through the clearances in the separable joints in its shell amounts to 0.5 — 1 liter(s)/minute. With more stringent process control, the leakage can be reduced to 0.3 — 0.6 liter(s)/minute.

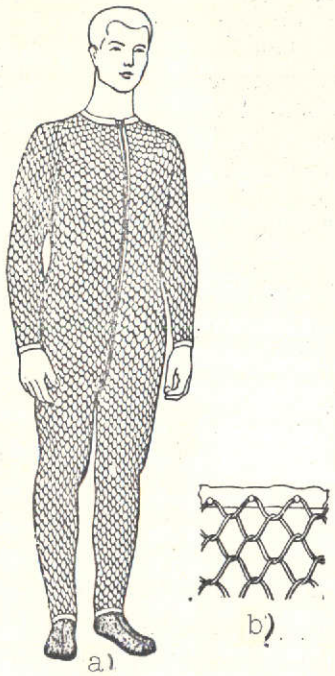


Figure 5.5. Shell restraint layer fabricated from netting.

a — general view; b — threat weaving scheme.

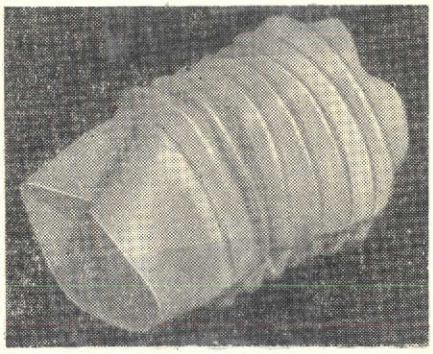


Figure 5.6. Pressure suit elbow hinge fabricated from latex rubber by dipping method.

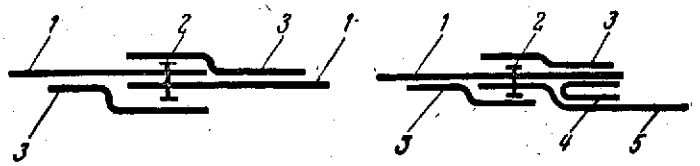
The hermetic layer is fabricated from sheet rubber about 1 mm thick. The front opening in this layer is sealed by an appendix. The hermetic shell can also be made from latex rubber by dipping into a latex solution.

Specifically, Figure 5.6 shows the knee hinge of a hermetic /142 shell made from latex rubber about 0.5 mm thick.

Of interest is the *vapor conducting (vapor permeable) hermetic shell*, which eliminates the necessity for ventilating the pressure suit to remove water vapor.

At the present time, research studies are being made to develop such a shell, specifically one based on a polyurethane thermoplastic resin material.*

*Bixler, H. J., A. S. Hofman and L. A. Spano. New Polymeric Material Holds Key to Pervaporative Space Suit Cooling. Space/Aeronautics, Vol. 48, No. 7, 1967.



Figures 5.7 and 5.8. Typical seams for single layer pressure suit shells made from rubberized fabric.

1 — rubberized fabric; 2 — threads; 3 — rubberized fabric overlayer; 4 — regulator tape (single layer rubberized fabric); 5 — appendix fabric (single layer rubberized fabric).

The single-layer shell is made from airtight fabric having the required strength.

The fabric is cut to patterns, then the individual parts — which have been cut out — are bonded together and stitched. To ensure seam hermeticity, two strips of rubberized fabric are applied and bonded to the seam after sewing.

Typical seam constructions for single-layer shells made from rubberized fabric are shown in Figure 5.8. The strength of the sewn seams is verified by static tests of specially prepared samples.

The maximum strength of the sewn seam usually does not exceed 80 — 90% of the basic fabric strength; the minimum strength decreases because of possible processing defects to 60 — 70% [4].

Rubberized fabrics whose strength characteristics are shown in Table 8.3 have been used to fabricate single-layer pressure suit shells. The high labor content in fabricating shells from such fabrics and their comparatively low strength in operation have led to changeover to multilayer shells.

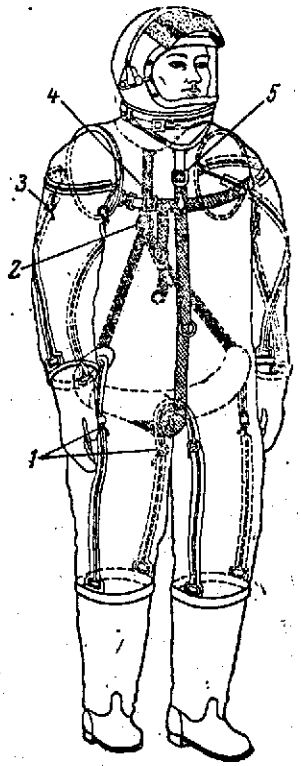


Figure 5.9. Typical pressure suit restraint system [2].

1 — buckle for regulating trouser length; 2 — buckle for regulating suit body length; 3 — buckle for regulating sleeve length; 4 — transverse tensioner; 5 — buckle for tightening helmet.

The restraint and tensioning system limits the shell volume increase due to the internal differential pressure in the pressure suit and permits fitting the suit to the individual's body. This system consists of a system of cables or strong cords and straps (Figure 5.9).

The restraint system design may be either integrated or separate.

In the integrated restraint system, both body length and helmet position (preload) are regulated simultaneously (see Figure 5.75). In the individual restraint system, the suit body length is regulated independently of helmet position. /143

Fitting of the suit can be accomplished by the pilot on his own.

Adjustment of sleeve and leg lengths is provided in order to fit the suit to the individual.

The pressure suit separation points must provide comparatively rapid donning and doffing of the suit. Usually, the emergency-survival pressure suits have a neck joint, joints for

the gloves, and a chest opening. On some suit models, there is also a joint for the footwear.

The pressure suit shells are made in several standard sizes (lengths), and fitting is accomplsiehd with the aid of the restraint system, the locks and buckles of which usually permit regulating the dimensions of the suit parts in accordance with the dimensions of the torso, hips, legs, and arms.

Table 5.1 shows the characteristic male dimensions adopted in the garment industry.

Reduction of the number of standard sizes leads to increase of the folds used for fitting, and in the final analysis to deterioration of man's mobility in the pressure suit. Therefore, in the most critical cases, space flights for example, the shells are made individually to the anthropometric dimensions of each cosmonaut.

Conventional flight clothing for pilots is made in six sizes (46, 48, 50, 52, 54, 56) and six lengths (155 — 160, 161 — 166, 167 — 172, 173 — 178, 179 — 184, and more than 184 cm).

From one to three lengths are made for each of the indicated sizes. The garment size is defined as half the chest circumference in centimeters (measuring tapes must be applied under the arms) with underwear and shirt on.

Strength Design of Pressure Suit Restraint Shell

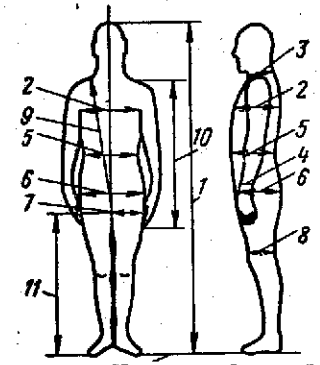
The pressure suit restraint shell under internal differential pressure is capable of withstanding the normal tensile running loads which arise from the tensile forces applied to the

TABLE 5.1

TYPICAL MALE MEASUREMENT DATA

Size & length	Height, cm	Male girth dimensions, cm								Length, cm	
		Chest	Neck	Wrist	Waist	Buttocks	Hips	Thigh	Torso	Arm	Leg
	1	2	3	4	5	6	7	8	9	10	11
48—1	161—167	92—96	38—39	17—18	76—80	87—91	50—53	35—36	155—160	73—76	78—81
50—2	167—173								160—165	76—78	81—84
50—3	173—179	96—100	39—40	17—18	80—83	91—95	53—55	36—38	162—167	78—81	84—87
50—4	179—185								165—170	81—83	87—90
52—2	167—170								162—167	76—78	81—84
52—3	173—179	100—104	40—41	17—18	83—87	95—99	55—58	38—39	165—170	78—81	84—87
52—4	179—185								167—172	81—83	87—90
54—2	167—173								165—170	76—78	81—84
54—3	173—179	104—108	41—42	17—18	87—90	99—103	58—60	39—41	167—172	78—81	84—87
54—4	179—185								170—175	81—83	87—90
56—3	173—179	108—112	42—43	18—19	90—94	103—107	60—63	41—42	170—175	78—81	84—87
58—4	179—185	112—116	43—44	18—19	94—97	107—111	63—65	42—44	175—180	81—83	87—90

Measurement diagram



shell, and the tangential shear or torshion stresses from the tensile forces. Thus, the shells may be considered a prestressed structure.

If a failure occurs in the shell, the slit which forms will open up under the influence of internal pressure, and in order to bring the two edges together, it is necessary to apply two equal and oppositely direct forces, which are running loads in kG/cm or kG/m.

In regard to construction, the shells are divided into the *carcass* and *non-carcass* types. Various restraint elements (straps, tapes) which take longitudinal or transverse loads are used as the carcass.

In order to determine the stresses in a shell subject to differential internal pressure, we shall examine equilibrium of the forces applied to an infinitely small fabric element cut from the shell (Figure 5.10).

The equation characterizing equilibrium of the forces acting on the element will have the form

$$pdS_{\text{I}}dS_{\text{II}}=2T_{\text{I}}dS_{\text{II}}\sin\frac{d\varphi_{\text{I}}}{2}+2T_{\text{II}}dS_{\text{I}}\sin\frac{d\varphi_{\text{II}}}{2},$$

where T_{I} and T_{II} are the unknown running loads in kG/m, p is the internal pressure.

Considering that $dS_{\text{I}}=r_{\text{I}}d\varphi_{\text{I}}$, $dS=r_{\text{I}}\ d\varphi_{\text{II}}$ and that the sines of the small angles $d\varphi_{\text{I}}/2$ and $d\varphi_{\text{II}}/2$ can be considered equal to the angles themselves, the equilibrium equation takes the form /145

$$pdS_{\text{I}}dS_{\text{II}}=\left(\frac{T_{\text{I}}}{r_{\text{I}}}+\frac{T_{2}}{r_{\text{II}}}\right)dS_{\text{I}}dS_{\text{II}}, \qquad (5.1)$$

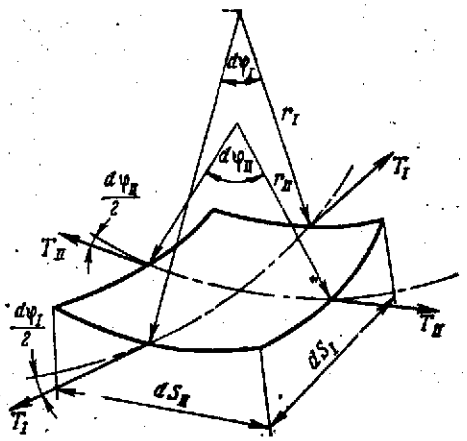


Figure 5.10. Illustration for deriving the equation of equilibrium of the forces applied to a pressure suit shell element subject to differential pressure.

hence

$$p=\left(\frac{T_I}{r_I}+\frac{T_{II}}{r_{II}}\right).$$

In the sphere case $r_I = r_{II} = R$ and therefore

$$T_I=T_{II}=pR/2. \qquad (5.2)$$

In a cylinder $r_{II} = R$; $r_I = \infty$, therefore

$$T_I=pR/2, \qquad (5.3)$$

$$T_{II}=pR. \qquad (5.4)$$

For a conical shell

$$T_{II}=2T_I=pR\frac{\cos\alpha}{2}, \qquad (5.5)$$

where α is the taper angle.

The allowable shell material running stresses T_{all} are usually expressed as fractions of the ultimate stress T_{ult} corresponding to uniaxial loading with account for the safety factor, namely

$$T_{all} = T_{ult}/n, \qquad (5.6)$$

where n is the safety factor, accounting for weakening of the material in biaxial loading, the material fatigue characteristics,

and possible weakening in the seams (usually we take n = 3).

It is obvious that the magnitude of the coefficient n must be considered in converting from the working pressure in the suit to the design pressure.

For example, let us determine the loads which arise in a shell with design differential pressure $\Delta p = 1.2$ kG/cm^2 and diameter of the cylindrical part of the shell d = 600 mm.

We find the normal running stresses from (5.3) and (5.4)

$$T_{ax} = \Delta p \frac{d}{4} = 1.2 \cdot \frac{60}{4} = 18 \quad \text{kG/cm};$$

$$T_{tr} = \Delta p \frac{d}{2} = 1.2 \cdot \frac{60}{2} = 36 \quad \text{kG/cm}.$$

In case of ejection from a spacecraft at high flight speed, the pressure suit experiences loading from the velocity head of the relative airstream. The shell is compressed under the action of the velocity head and the internal pressure in the suit increases. It has been established experimentally that the internal pressure increase can reach 80% of the velocity head pressure [2].

If the indicated flight speed (v_i) at which ejection is expected is specified, then the true speed (v_H) is determined from the well-known formula /146

$$v_i = v_H \sqrt{\varrho_H/\varrho_0} = v_H \sqrt{\Delta_H}, \qquad (5.7)$$

where ϱ_H is the air density at height H; ϱ_0 — air density at sea level; $\Delta_H = \frac{\varrho_H}{\varrho_0}$ — relative density at height H.

Hence the velocity head

$$q=\rho_H v_H^2/2=\rho_0 v_i^2/2. \tag{5.8}$$

Formula (5.8) can be transformed

$$q=\frac{v_i^2}{207}, \tag{5.9}$$

for v_i in km/h, or $q = 9.5p_H M^2$, where M is the Mach number ($M = v_H/a_H$, here a_H is the speed of sound at height H).

Woven materials are anisotropic and do not follow Hooke's law and the principle of independence of force action. In such materials, the magnitude of the Poisson coefficient depends on the stress state. Therefore, fabric deformation in any direction depends on the relationship of the loads acting in the warp and woof directions.

The warp and woof threads form grids of some form or other, depending on the nature of the thread interweaving.

In strength calculations of a fabric construction, it is necessary to take into account the fabric strength loss due to working in two directions (in the warp and woof directions). Under the action of an applied load, some wavy threads tend to straighten and, consequently, increase the wave height of the other threads, causing additional stresses in the latter.

In contrast with metals, as a rule fabrics under load have different elongations in different directions, therefore, their deformations depend significantly on the relationship between the magnitudes of the running loads acting in mutually perpendicular directions. The magnitudes of these elongations are

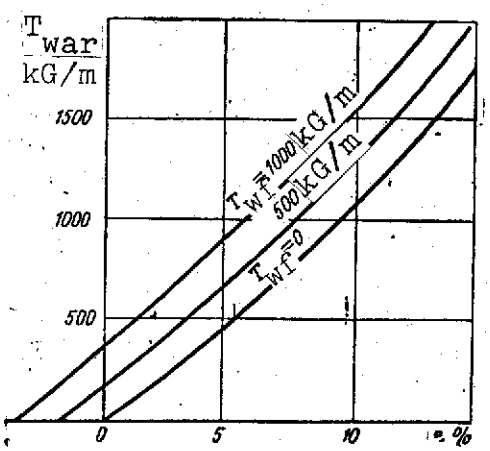


Figure 5.11. Diagram of dacron fabric elongation in warp direction for various constant woof loading conditions (T_{war}, T_{wf} are the warp and woof loads, ε — relative elongation [5]).

presented in the characteristics obtained in biaxial loading of an experimental fabric specimen.

For this purpose, a plane test specimen having the form of a cross is loaded along the ends by forces acting in two mutually perpendicular directions (along the warp and woof threads). A square whose side deformations are recorded under load is marked in the central part of the specimen.

The characteristic of woven fabric material in biaxial loading is usually given in the form of diagrams similar to that shown in Figure 5.11.

For fabrics, we usually take a linear relation between load and deformation, which is valid only within the limits of small (on the order of 5%) material relative elongations. /147

Studies made by Strekozov [5] have shown that, for kapron fabrics with elongations on the order of 20%, the tensile curve can be approximated quite accurately by a quadratic relation of the form $T_1=E_1\varepsilon_1+E_1'\varepsilon_1^2+\nu_{21}T_2; T_2=E_2\varepsilon_2+E_2^1\varepsilon_2^2+\nu_{12}T_1$, where $E_1, E_1^1, E_2, E_2^1, \nu_{12}, \nu_{21}$ are constant coefficients of the material which can be determined from the tensile curve approximation; T_1, T_2 — principal loads; $\varepsilon_1, \varepsilon_2$ — principal elongations.

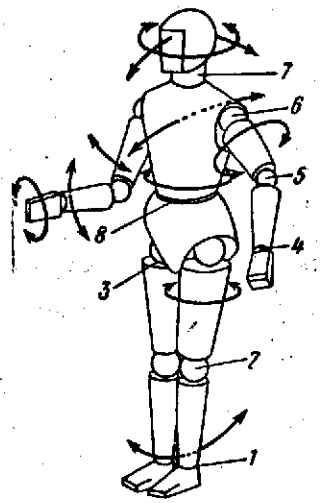


Figure 5.12. Diagram of motions which must be provided for man in pressure suit.

1 — ankel joint; 2 — knee joint; 3 — hip joint; 4 — wrist joint; 5 — elbow joint; 6 — shoulder joint; 7 — neck joint; 8 — waist joint.

The ultimate strength of fabrics in biaxial loading is usually determined by tests of cylindrical or spherical models fabricated from the fabrics. Experiments have shown that fabric strength in biaxial loading amounts to 0.4 — 0.6 times the fabric strength in uniaxial loading [5].

Pressure Suit Mobility

Mobility is one of the basic criteria defining pressure suit quality. Figure 5.12 illustrates the various motions of man's body and extremities which must be provided in the pressure suit. The forces required to perform such motions must not tire the wearer excessively.

It should be noted that the magnitude of these forces is inversely proportional to their application duration and repetition frequency. Man may not have great strength but he can maintain some moderate effort in the course of a long time period. The muscle force, i.e., the force of a muscle per square centimeter cross section, is about 10 kG on the average [6].

The magnitudes of the forces developed by man's arm are shown in Figure 5.13.

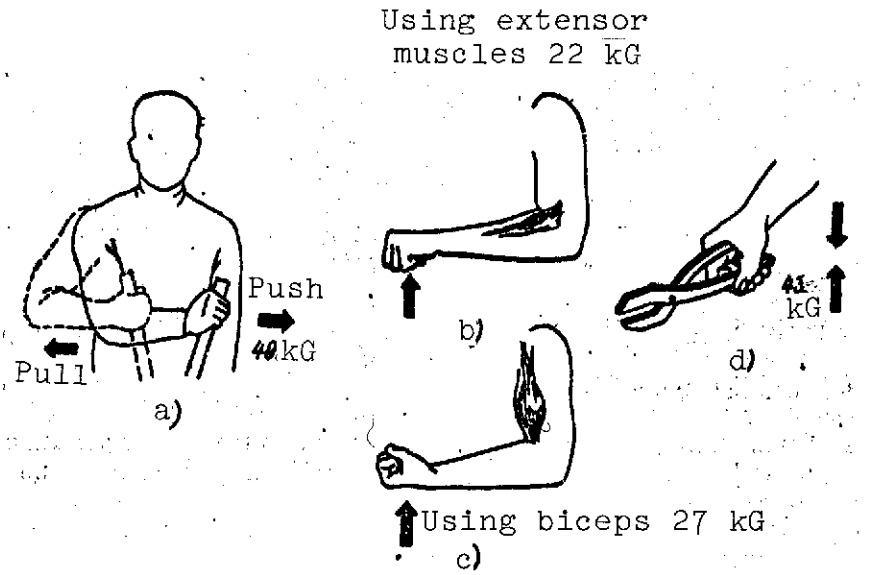


Figure 5.13. Magnitudes of forces developed by man's arm.

In the case of transverse motions of the arm bent at the elbow joint, the force developed by a man pushing is greater than when pulling.

The magnitude of the maximum moment created during rotation of the wrist of the right hand to the right is equal to about 0.65 kG/m, in practice it is recommended that this moment be limited to a magnitude of 0.14 kG/m.

When turning the wrist to the left, the maximum moment is 1 kG/m. It is recommended that this moment be limited to a magnitude of 0.15 kG/m for practical purposes [7].

Figures 5.14 and 5.15 illustrate the forces developed by a man for various movements [6].

The pressure forces developed by the foot on a pedal are shown in Figure 5.16. When straightening the leg, it is possible to develop briefly a force of up to 205 — 230 kG by pushing the spine against the back of the chair [8].

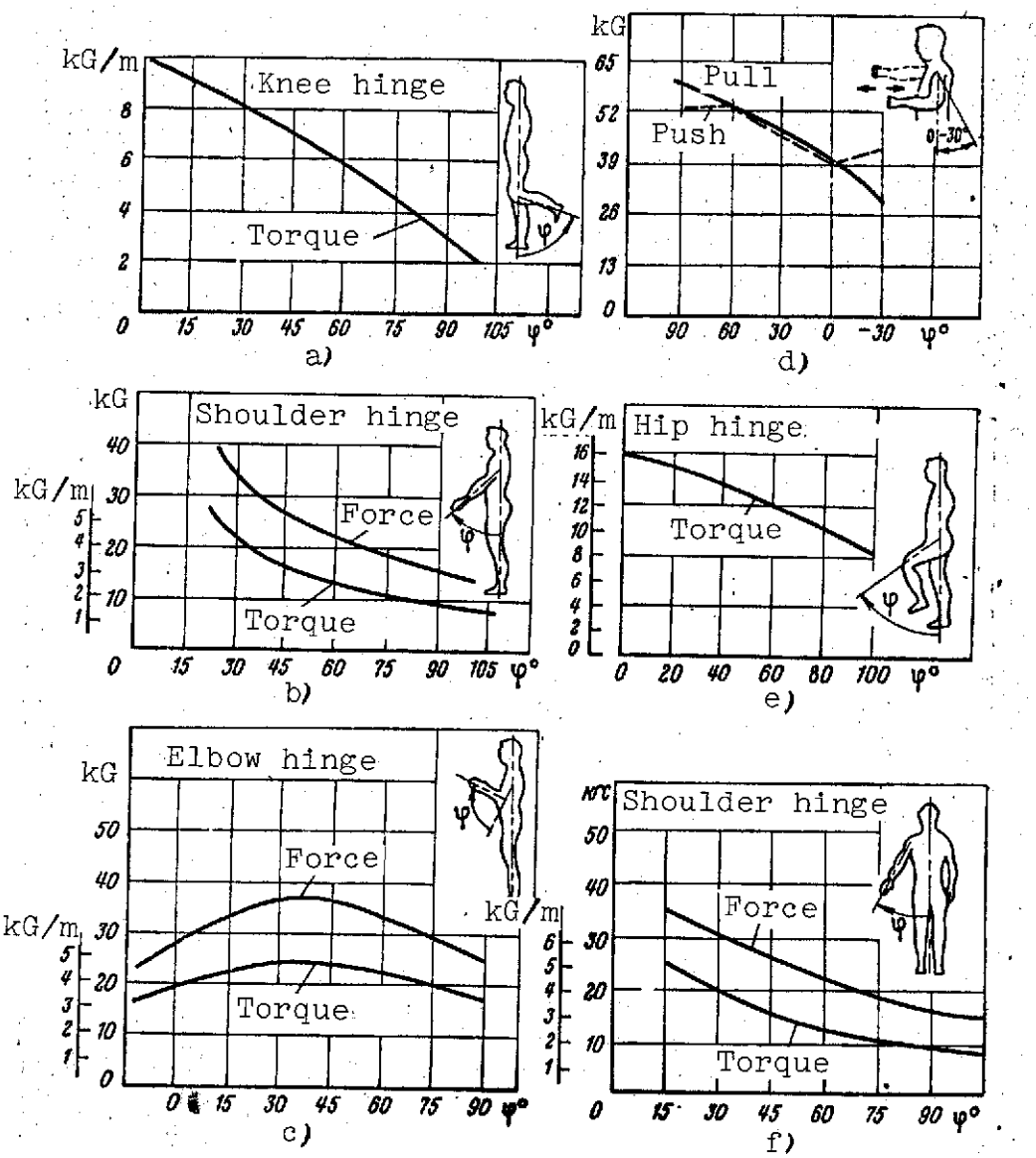


Figure 5.14. Forces and moments developed by man [8].

a — leg flexion in knee joint; b — arm rotation in shoulder joint; c — arm flexion in elbow joint; d — pushing with right hand; e — leg flexion in hip joint; f — arm abduction in shoulder joint.

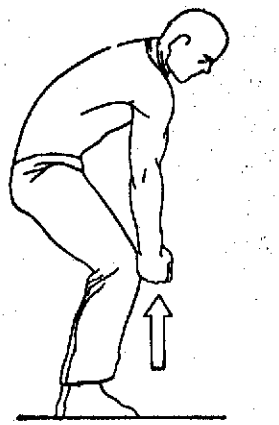


Figure 5.15. Lifting force of body and arm when straightening [6].

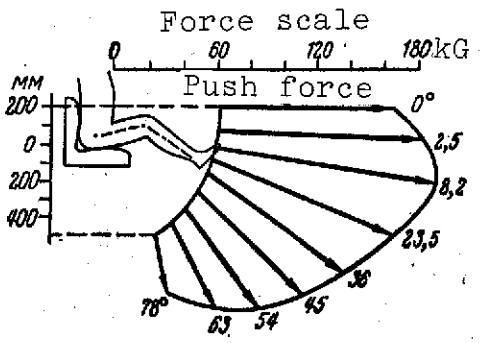


Figure 5.16. Diagram of leg push forces on pedal [8].

Joints are used to provide man with mobility in the pressure suit: shoulder, elbow, knee, in the ankle, finger, and palm regions. Joint constructions in pressure suits are varied and depend on the nature of the motions being accomplished using these joints. For example, the hinges which provide /148 movement of man's knee joint are structurally less complex than the shoulder joint hinges.

The hinge designs must first of all limit man's movement as little as possible. At the same time, the hinges must be as simple as possible in construction and well fitted.

According to the recommendations of physiologists, the allowable value of the bending moment should not exceed 20% of the maximum moment which a man can develop. $M_{m\ all} = 0.2\ M_b$, where $M_{m\ all}$ is the allowable moment for a man when flexing the joint through a definite angle φ.

Table 5.2 shows the values of $M_{m\ all}$ for the various joints.

TABLE 5.2

FORCES DEVELOPED BY MAN [6]

Joint	Motion	Bend angle degrees	Torque developed by man	
			Maximum kG/m	Minimum kG/m
Knee	Flexion Extension	0 — 100	10	2
Shoulder	Flexion Extension	0 — 90	5.5	1.8
Hip	Flexion Extension	0 — 100	16	8
Elbow	Flexion Extension	0 — 90	5	3.5
Shoulder	Abduction Adduction	0 — 90	5	1.8

Pressure Suit Hinges /149

The hinge designs in use at the present time provide bending in a single plane, rotation, and also rotation and bending in one and two planes (combined hinges).

Hinges providing bending in a single plane are widely used in pressure suits, since they are simple to fabricate and meet the requirements imposed on them (Figure 5.17).

The hinge, usually termed an "accordion," is made so that the shell fabric performs the role of the outer restraint layer and a convoluted rubber insert is used for pressure sealing. The axial forces are taken by a tension element built directly into the hinge structure. The mobility of the convoluted hinge /151 depends on the geometry of the convolutions which form it.

Figure 5.17. Corrugated pressure suit knee joint (buckles for regulating trouser length can be seen).

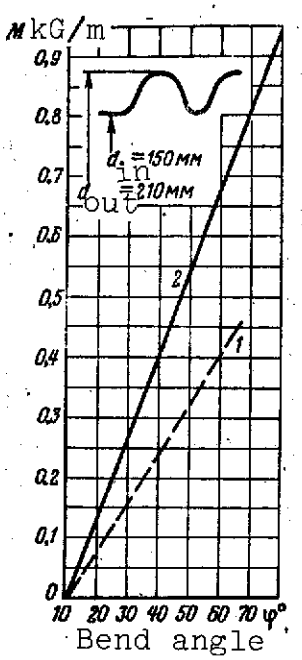


Figure 5.18. Torque required to flex "accordion" type joint with 12 corrugations as function of bend angle (specimen length 360 mm) [14].

1 — with differential pressure 0.2 kG/cm^2; 2 — with differential pressure 0.4 kG/cm^2.

In construction, the convolutes may be:

— isolated, when each convolute is separated from the adjacent convolutes by cylindrical inserts so that when the shell bends, the convolutes do not come into contact with one another;

— constrained, when neighboring convolutes are in contact with one another;

— semi-constrained, when each convolute is restricted by a neighboring convolute on one side only.

In Figure 5.17, the end convolutes are semi-constrained, and all the intermediate convolutes are constrained. The curves of moments required to bend the "accordion" hinge with constrained

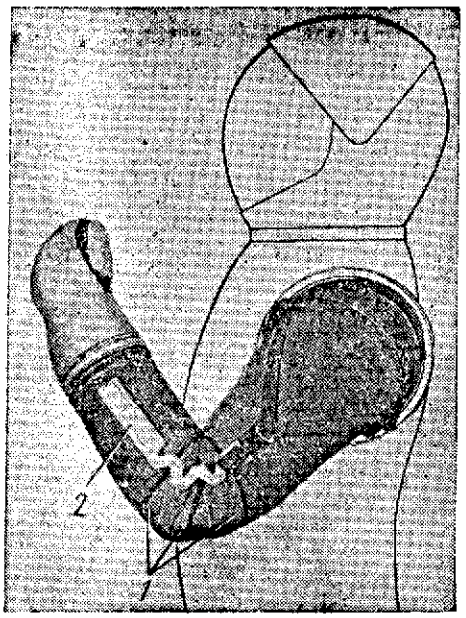


Figure 5.19. Pressure suit elbow hinge with three "orange peels."

1 — "orange peels"; 2 — restraint strap guide.

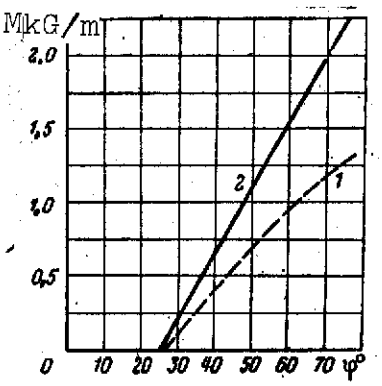


Figure 5.20. Curves of torques necessary to bend joint with "orange peels" when rotating through angle φ (inside diameter 150 mm).

1 — with differential pressure 0.2 kG/cm^2; 2 — with differential pressure 0.4 kG/cm^2.

convolutes are shown in Figure 5.18 as a function of bend angle.

The hinge with "orange peels" [hinge consisting of elements similar to orange slices (peels)] operates well in bending in a single plane (Figure 5.19). The "orange peels" are made from the same material as the shell restraint material.

The curves of the moments required to bend the hinge with "orange peels" through the angle φ for different differential pressures in the suit are shown in Figure 5.20.

Hinges formed by gathering the fabric at the bend locations are simple to fabricate and are used in pressure suits to provide mobility of the arms and legs (Figure 5.21). However, folds may form during bending which press on the body and cause discomfort.

Figure 5.21. Suit with swivelling helmet and elbow and knee joints formed by fabric gathers.

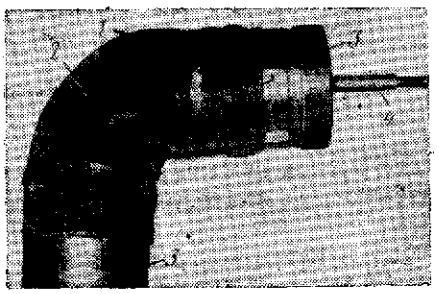


Figure 5.22. Joint with gathers (bending performed on an instrument which measures the torques required).

1 — tension strap; 2 — guide strap; 3 — flange; 4 — bending mechanism drive.

Figure 5.22 shows an experimental model of a suit with gathering of the material, fabricated for conducting tests, and Figure 5.23 shows the bending moment diagram. In this hinge, the axial loads are taken by the tension element 1, built into the guide strap 2. The degree of tension is adjusted by lengthening or shortening the tension element 1.

Swiveling hinges which provide rotational movement are used in most cases in the neck, shoulder, and wrist joints. Hermetic bearings are most widely used in such hinges. /153

The configuration of a shoulder hermetic bearing is shown in Figure 5.24. It consists of the outer ring 6, inner ring 5, and the sealing system. Sealing of the bearing is provided by air pressure in the suit, which forces the rubber flapper valve 2 against the ring 6. If we neglect the friction forces which

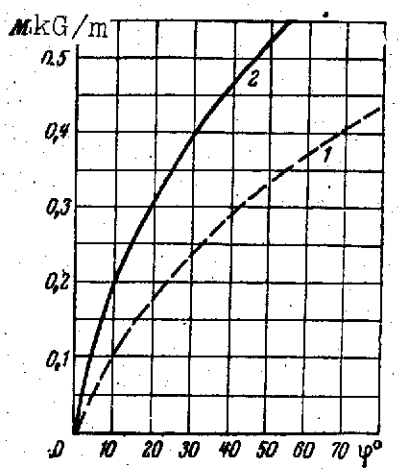


Figure 5.23. Curves of torque necessary to bend joint with gathers for various bend angles (initial circle diameter 150 mm).

1 — with differential pressure 0.2 kG/cm^2; 2 — with differential pressure 0.4 kG/cm^2.

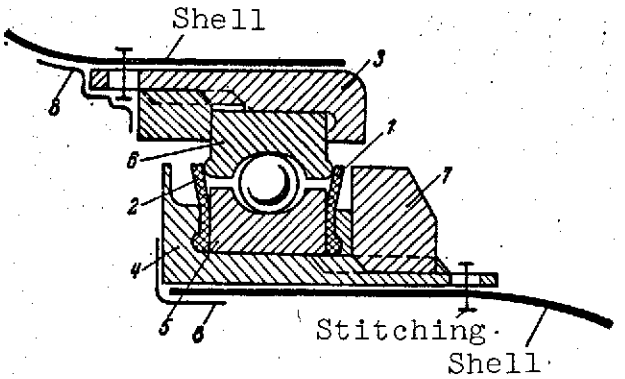


Figure 5.24. Arrangement of pressure suit shoulder hermetic pivoting bearing.

1 — outer flapper valve which seals against water penetration; 2 — inner flapper valve which seals against air penetration; 3 — bearing outer race; 4 — inner race; 5 — bearing inner ring; 6 — bearing outer ring; 7 — clamping nut; 8 — sealing strip.

arise during rotation of the balls the moment required for bearing rotation is found from the equation

$$M = rfS\Delta p, \qquad (5.11)$$

where r is the bearing radius, f — friction coefficient; S — area of flapper contact with the ring; Δp — differential air pressure in the suit.

During assembly of the bearing, the outer ring is heated and "seats" freely on the balls.

Combined flapper valves made from different materials are used in the rotating bearings to reduce the magnitude of the torque required. For example, in the bearing shown in Figure

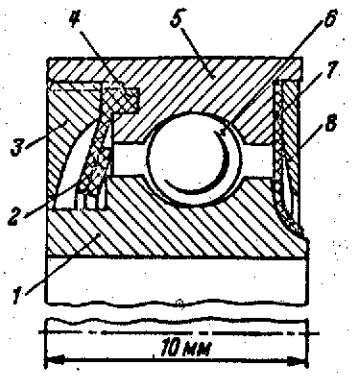


Figure 5.25. Pressure suit rotating hermetic shoulder joint with seal.

1 — teflon inner ring (stationary); 2 — teflon valve; 3 — nut; 4 — rubber valve; 5 — outer ring (movable); 6 — bearing ball; 7 — rubber valve; 8 — clamping ring.

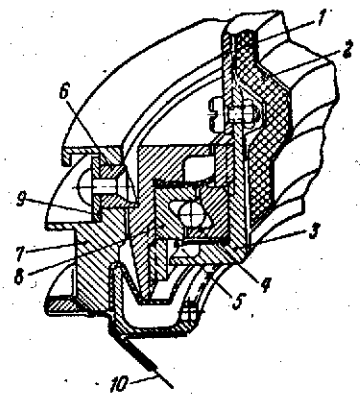


Figure 5.26. Suit rotating hermetic neck bearing.

1 — helmet shell; 2 — thermal insulation layer; 3 — bearing race; 4 — bearing ring; 5 — helmet sealing valve; 6 — helmet attachment latch; 7 — suit neck ring; 8 — bearing outer race; 9 — expansion ring (race); 10 — shell bow.

5.25, the friction coefficient is reduced to 0.04 for a teflon-steel pair. The bearing provides practically complete pressure sealing. Air leakage amounts to only hundredths of a liter per minute.

The arrangement of a neck hermetic pivoting bearing is shown in Figure 5.26.

The wrist hermetic pivoting bearing shown in Figure 5.27 is connected with the glove and cuff disconnect. Its inner disconnect ring consists of two rings (6 and 12). The thread provided on ring 12 permits compressing the balls against the outer ring 2, thereby eliminating play between the rings.

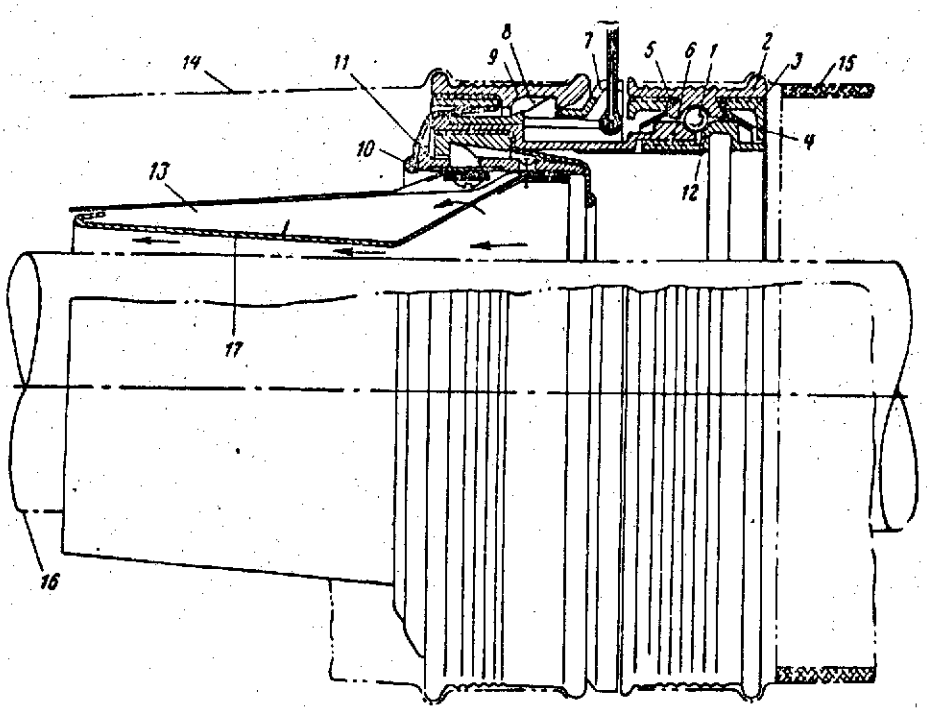


Figure 5.27. Suit pivoting wrist hermetic bearing.

1 — bearing ball; 2 — outer ring; 3 — clamping nut; 4 — inner valve; 5 — outer valve; 6 — inner ring; 7 — locking ring; 8 — spring ring (with strap); 9 — glove ring; 10 — glove seal; 11 — cuff ring; 12 — bearing ring; 13 — cuff; 14 — glove; 15 — suit shell; 16 — arm; 17 — cuff rubber ring.

Figure 5.28 shows a pressure suit with seven hermetic rotating bearings, each of which consists of two rings and profiled rubber sealing flapper valves.

Combined hinges are combinations of two hinges which provide rotation and bending or bending in two planes.

One such hinge (shoulder) is shown in Figure 5.29. It /155
has good mobility and offers practically no restriction to arm movement. The soft part of the hinge consists of three fabric "orange peels," the hard part is a rotating hermetic

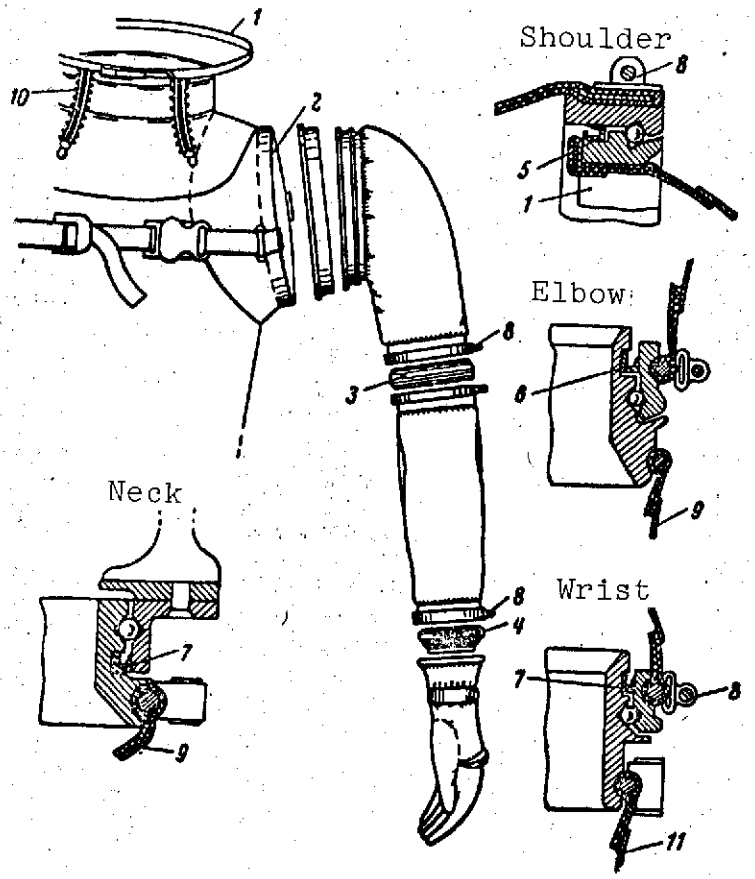


Figure 5.28. Suit with family of pivoting hermetic bearings.

1 — neck; 2 — shoulder; 3 — elbow; 4 — wrist; 5, 6, 7 — sealing valves; 8 — tension strap; 9 — suit shell; 10 — neck zipper; 11 — glove.

bearing. A combined shoulder hinge was shown in Figure 5.2. In this hinge, flexure of the arm in the shoulder joint takes place by compression of the convolutes while rotation takes place by displacement of the cable along the teflon guide sleeves (to reduce the friction).

A combined hinge which provides bending in two planes is shown in Figure 5.30. In this hinge, the conventional tensioning straps are replaced by cables and a system of rollers.

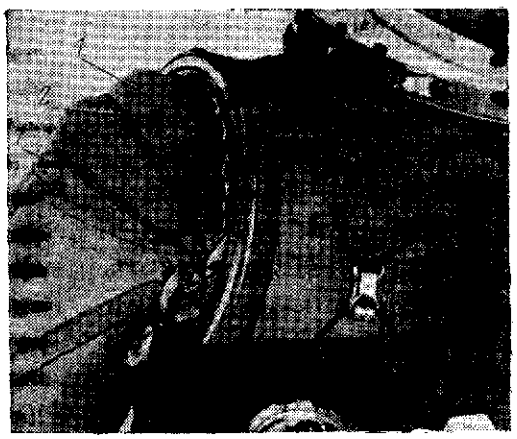


Figure 5.29. Combined pressure suit shoulder joint.

1 — "orange peels"; 2 — transverse tension strap.

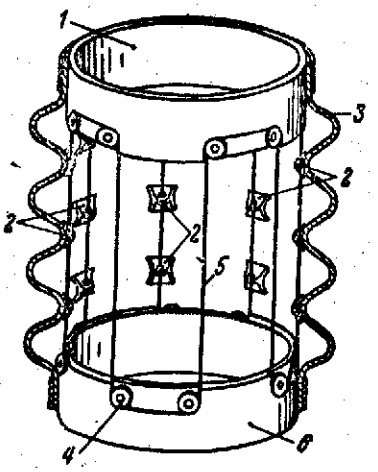


Figure 5.30. Combined pressure suit joint providing bending in two planes.

1 — upper ring; 2 — guide cable; 3 — corrugated hinge; 4 — guide rollers; 5 — cable; 6 — lower ring.

3. Pressure Suit Helmet

The pressure suit helmet must provide:

— the required vision for the wearer and protection for his eyes from the blinding action of the sun;

— protection of the head against possible impacts and also against overheating and overcooling;

— supply of breathing oxygen and removal of respiration products from this oxygen.

The pressure suit helmet made in accordance with the anthropometric dimensions of the head will have the lowest possible weight and sufficient strength and will reduce the level of external noise which penetrates the helmet. The pilot must be able to remove and put on the helmet without outside assistance. /157

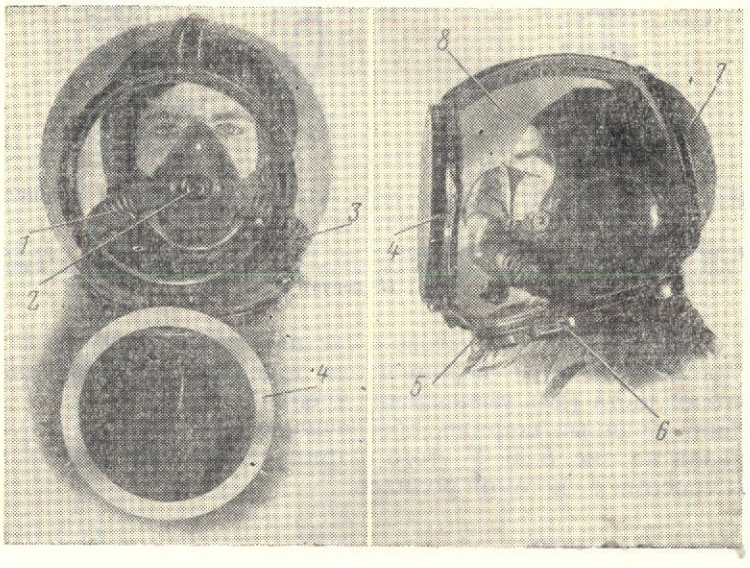


Figure 5.31. Removable bubble helmet of mask type pressure suit. 1 — inhalation hose; 2 — liquid food intake valve; 3 — exhalation hose; 4 — faceplate; 5 — neck ring; 6 — helmet latch; 7 — soft fabric part of helmet; 8 — helmet glass.

Helmet weight is an important factor characterizing helmet operational characteristics. In the absence of pressure in the suit, the helmet rests on the pilot's shoulders and causes discomfort. A helmet weighing more than 2.5 kG is considered heavy.

The existing helmet designs are subdivided into nonswiveling *(bubble)* and swiveling *(rotating)* types.

The bubble helmet is stationary and can be either removable or nonremovable. It has comparatively large dimensions (300 to 320 mm in diameter) for rotation of the head inside the helmet even with an oxygen mask worn on the face (Figure 5.31). A nonremovable bubble helmet was used in Gagarin's pressure suit (see Figure 5.76).

The swiveling helmet is retained by clamps, rotates in a hermetic bearing together with rotation of the head, and is mounted on the neck ring of the pressure suit shell. When there is no differential pressure in the suit, the swiveling helmet offers very little resistance to rotation of the head. The resistance to rotation increases when there is pressure in the suit. The swiveling helmet may be separated by a face seal into a front section which is filled with oxygen and a rear section which communicates with the space beneath the suit shell which is ventilated by air. In order to prevent drawing air from the rear section, the pressure in the front section is higher by 20 — 30 mm Hg than that in the rear section. The respiration products are removed from the helmet through the exhalation valve.

The presence of the face seal reduces the oxygen flow required for helmet ventilation (removing the respiration products) and head cooling is improved.

Helmet strength is verified in static tests together with the pressure suit and separately in dynamic tests.

With increase of the flight velocity of modern flight vehicles, it has become necessary to protect the pilot's head against impact during takeoff, in flight, and during landing (especially emergency landing). Impacts with protruding parts of the cabin cause serious damage to the skull bone structure and loss of consciousness.

Special studies of the load factor tolerance limits of the various parts of the body have shown that man's head protected by a strong helmet can withstand:

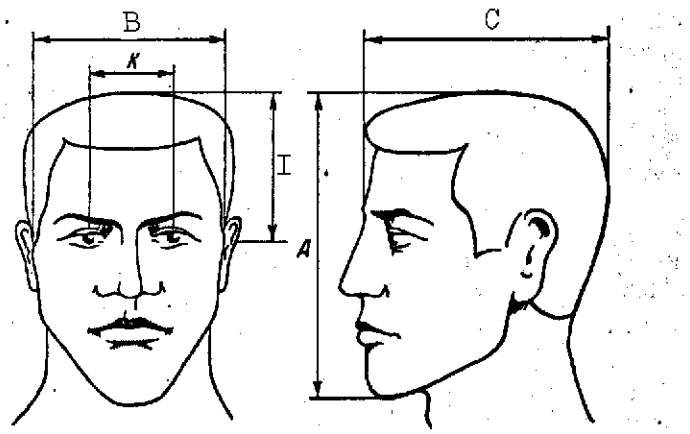


Figure 5.32. Characteristic dimensions of male head [7].

— frontal impacts of 38 g;

— side impacts of 25 g;

— aft impacts of 35 g.

These tests were conducted in the USA with volunteer subjects who tolerated these loads without any damage to the skull or indications of brain concussion.

The principal elements of the helmet structure are: shell, visor, light filter.

The helmet shell is made of a strong material (AMg-3 aluminum alloy or fiberglass cloth) having the required impact strength.

A demountable ring is attached to the lower ring of the shell and when donning the helmet, is connected with a mating neck ring mounted on the suit shell.

The characteristic dimensions of the male head are shown in Figure 5.32 and Table 5.3.

TABLE 5.3

CHARACTERISTIC DIMENSIONS OF MALE HEAD [7]

Measured quantity	Notations in Figure 5.32	Dimensions in mm			Dimensions in mm for 95% of measurements	
		10%*	90%*	Mean	Max	Min
Circumference	—	551	551	—	—	—
Height	A	—	250	228	254	193
Width	B	144	159	155	172	137
Fore-aft	C	186	203	196	211	175
Crown to eye	I	99	130	113	136	86
Pupil spacing	K	61	68	—	—	—

*Percent of total number of individuals measured.

The free diameter of the (inner) demountable ring with account for the seal must be no less than 260 mm. The inside of the shell is coated with a layer of thermal and sound insulating material (foam rubber, porolon, or foam plastic 20 — 30 mm thick) and a knit fabric liner. This entire packet reduces markedly the level of the external noise which penetrates the helmet (see Table 2.7). /158

In engineering calculations, it is customary to use the degree of sound insulation (SI) of a structure, determined from the formula

$$SI = 10 \lg 1/\tau, \qquad (5.12)$$

where τ is the coefficient of sound transmission.

The sound insulation can be calculated with adequate accuracy from the formula

$$SI = 14 + 12.5 \lg G, \qquad (5.13)$$

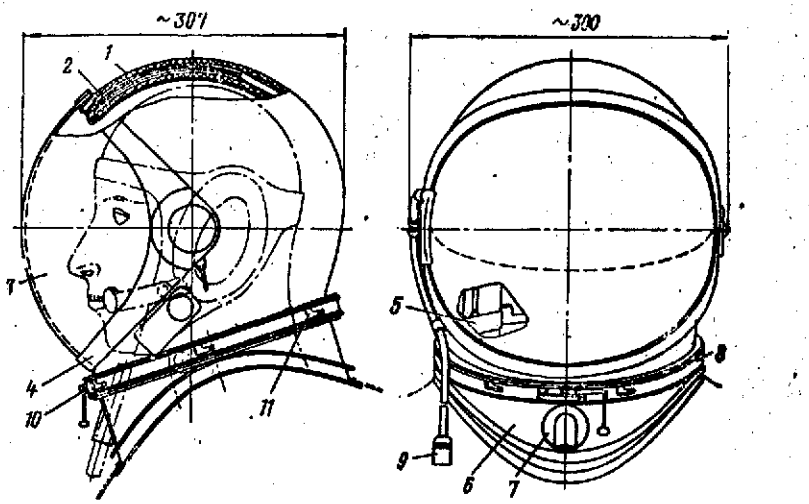


Figure 5.33. Pressure suit bubble helmet with electric glass heating and movable faceplate.

1 — shell; 2 — light filter; 3 — helmet glass; 4 — frame; 5 — ventilation device; 6 — transition part of neck ring; 7 — feeding valve; 8 — split ring; 9 — electric heating connector; 10 — lock (latch); 11 — bayonet lock.

where G is the weight per square meter of the sound insulating layer (kG/m^2).

Air supply into the helmet is provided through the ventilation device 5 (Figure 5.33). When the helmet is donned, the ventilating hose is connected with the pressure suit ventilation system and air is supplied through this hose to the helmet visor. This provides flow over the visor and prevents fogging. /159

The helmet visor can be stationary or movable (pivoting). The visual scan angles are determined by the visor dimensions and its location on the helmet.

In the bubble helmet, it is possible to increase the field of view by rotating the head inside the helmet.

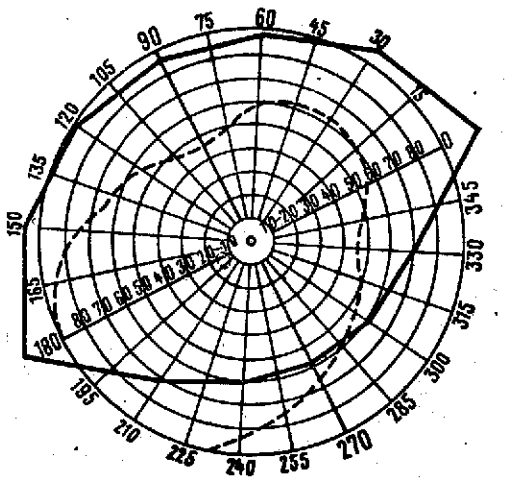


Figure 5.34. Zones of monocular and binocular viewing fields in pressure suit bubble helmet (dashed line is monocular field of view for left eye).

The normal field of view for the helmet is considered to be: 80° upward, 90° downward, and 250° to the sides.

When viewing with a single eye (monocular vision), correct depth perception is impossible. It is achieved only when viewing an object with both eyes (binocular vision).

The zones of monocular and binocular fields of view in a bubble helmet are shown in Figure 5.34.

The glass used for the helmet visor must be strong and have the required thermal stability and invariability of its optical properties. The optical properties can be evaluated on the basis of the following requirements:

— transparency or coefficient of light transmission in the visible portion of the solar spectrum no less than 90 — 92% for single glasses and about 85% for duplex and triplex glasses;

— angular deviation of the line of sight resulting from ray refraction, which depends on the nonuniformity of the glass thickness and curvature, no more than 10 — 12 min; /160

— distortion of shape of image viewed through the glass (image play) no more than 2 — 5 min;

— opaque for the biologically harmful portion of the solar spectrum with wavelength shorter than 350 nm;

— coefficient of light scattering no more than 5%.

Additional requirements are imposed on the space emergency-survival pressure suit helmet visor glass with regard to resistance to the action of vacuum and ionizing radiation.

The glass transparency is characterized by:

— the light transmission coefficient

$$\tau_\lambda = \frac{\Phi_{tran}}{\Phi_0} 100\%, \tag{5.14}$$

where Φ_{tran} and Φ_0 are, respectively, the light fluxes transmitted through the glass and incident on the glass;

— the reflection coefficient

$$\varrho = \frac{\Phi_{ref}}{\Phi_0} 100\%, \tag{5.15}$$

where Φ_{ref} is the light flux reflected by the glass;

— the absorption coefficient

$$\alpha = \frac{\Phi_{abs}}{\Phi_0} 100\%, \tag{5.16}$$

where Φ_{abs} is the light flux absorbed by the glass;

— the optical density of the glass

$$D_\lambda = \lg\left(\frac{1}{\tau_\lambda}\right) = -\lg \tau_\lambda. \tag{5.17}$$

Organic glasses (ST-1, SOL), polycarbonate, and triplex glass with electrical heating* are used for the visor glass.

Upon contact of the moist exhaled air with the helmet visor of the non-mask type pressure suit, fogging of the glass may occur if the temperature of its inner surface is below the dew point.

Double glass and electrical heating of the glass using a wire grid embedded in the glass or electrically conductive film are used to prevent fogging (Figure 5.35).

Data on the dew point as a function of temperature and relative humidity of the air are shown in Table 5.4.

When using double glass, its thermal resistance increases because of the air interlayer (10 — 15 mm) between the glasses. Permanent joining of the glasses is accomplished by bonding them together with a gasket (Figure 5.36). After bonding, the space between the glasses is purged with dry nitrogen through special holes (diameter 1 — 2 mm), which are then sealed over. The glass joint can also be made separable with the use of a rubber gasket.

The wire heating element is placed between two layers of organic glass. Butvar film is used as the bonding material. The wire diameter is 0.03 mm, spacing about 0.25 mm. Wire type electrical heating provides a temperature on the order of 30° C on the inner surface of the glass and protects the glass completely against fogging and icing (see Chapter 3 of [2]).

*Brief physico-mechanical properties of the materials used for helmet visors are presented in Chapter 8.

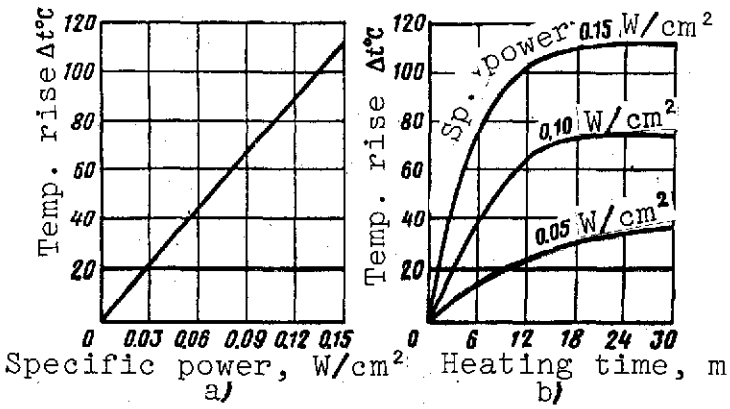


Figure 5.35. Characteristics of electrically heated glasses.

The glass temperature is regulated manually or automatically /161 by means of a rheostat. A miniature thermistor bonded into the glass serves as the temperature regulator automatic sensor.

The wire-grid heating elements reduce the visibility through the glass because of the diffraction effect which arises in the glass. The film type heating elements are free of this drawback.

The fixed visor can be sewn to the helmet by means of threads or can be joined by means of a metal cover plate (see Figure 5.36).

The movable helmet visor is lifted by a special attachment in the form of a bow (Figure 5.37). When this attachment is lowered, the glass is clamped against the helmet shell (Figure 5.38). Sealing of the glass is accomplished by a hollow rubber tube running along the perimeter of the visor. The sealing tube is compressed against the surface of the glass under the action of the differential internal pressure.

TABLE 5.4*

DEW POINT (see Chapter 4 of [15])

Air temperature ° C	Air relative humidity, %				
	60	70	80	90	100
+30	+20,9	+23,6	+25,9	+28,1	+30,0
28	19,0	21,7	24,0	26,1	28,0
26	17,2	19,8	22,1	24,1	26,0
24	15,3	17,8	20,1	22,1	24,0
22	13,4	15,9	18,1	20,1	22,0
+20	11,5	14,0	16,2	18,2	20,0
18	9,9	12,1	14,2	16,2	18,0
16	7,7	10,2	12,3	14,3	16,0
14	5,8	8,2	10,3	12,3	14,0
12	3,9	6,3	8,4	10,3	12,0
+10	2,1	4,4	6,4	8,3	10,0
8	+0,3	2,5	4,5	6,3	8,0
6	—1,5	+0,7	+2,7	4,4	6,0
4	3,2	—1,1	+0,7	2,5	4,0
2	4,9	3,0	—1,2	+0,5	2,0
0	6,5	4,6	2,9	—1,3	0,0
2	8,4	6,4	4,8	3,3	—2,0
4	10,3	8,3	6,7	5,3	4,0
6	12,1	10,3	8,7	7,3	6,0
8	13,9	12,2	10,7	9,3	8,0
—10	15,6	14,1	12,6	11,2	10,0

*Commas in the numbers indicate decimal points.

The light filter is provided to protect the eyes against the blinding and thermal effects of the solar rays.

The solar radiation spectrum on the Earth, to which man's eye has adapted, differs markedly from the spectrum beyond the limits of the Earth's atmosphere. This is explained by the fact /163 that the Earth's atmosphere serves as a filter which alters

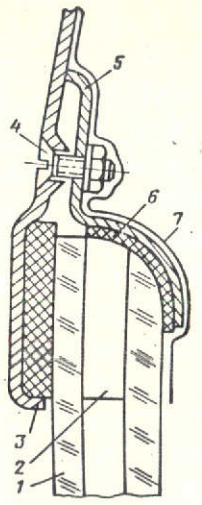


Figure 5.36. Unit for attaching glass to shell with the aid of metal cover plate.

1 — outer glass; 2 — interlayer; 3 — helmet shell; 4 — through bolt; 5 — metal cover plate; 6 — rubber seal; 7 — sealing fabric.

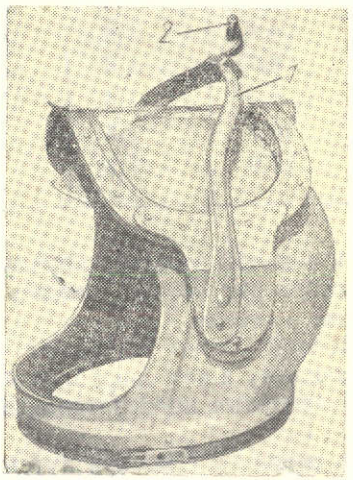


Figure 5.37. Suit helmet with pivoting hinge and liftable faceplate.

1 — faceplate lift bow; 2 — bow latch arm.

significantly the original solar spectrum. Therefore, the "unfiltered" solar radiation beyond the atmosphere is not safe for the unprotected eye. Calculations show that, even at a height of 50 km, the effect of solar radiation on the human eye in the course of a minute may damage the sight irreversibly (see Figure 1.1).

It is well known that, even at sea level, burning of the retina is observed in the course of a few minutes of direct exposure to solar rays. Particularly dangerous for the retina is the UV portion of the solar spectrum in the wavelength range from 250 to 320 nm.

During flights at comparatively low altitudes, where the biologically dangerous part of the solar spectrum is filtered out by the atmosphere, light filters are used to reduce the overall light flux passing through the helmet visor.

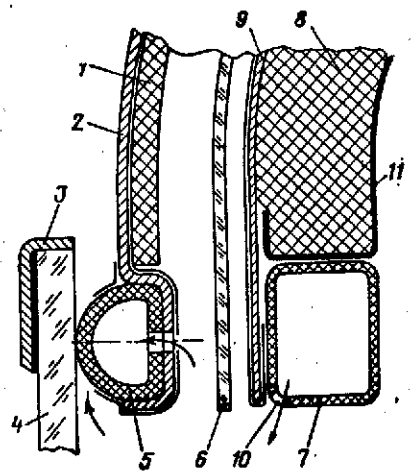


Figure 5.38. Sealing of helmet faceplate glass.

1 — interlayer; 2 — helmet shell; 3 — faceplate glass framing; 4 — faceplate glass; 5 — rubber tube for sealing; 6 — sliding light filter inside helmet; 7 — ventilating air hose; 8 — helmet sealing layer; 9 — gasket; 10 — hole for oxygen flow; 11 — underlayer.

Light filters are made from colored organic glass 2 — 5 mm thick. They are mounted outside and inside the helmet. Removable light filters which can be installed in case of necessity are also used.

The organic glass used for the visor does not in itself have the required light filtering properties. It can be given these properties by coloring the stock material or by applying a suitable coating on the outside surface.

The physico-mechanical properties and optical characteristics of some materials used in making light filters are presented in Chapter 8. A typical spectral characteristic of a light filter made from smoked glass is shown in Figure 5.39.

In order to protect the eyes during flight at high altitudes, the light filter must not only attenuate the solar light flux intensity, but also alter its spectral composition so that it will be analogous to the spectrum of solar light on the Earth, i.e.:

— not transmit to the eye the portion of the spectrum with wavelengths shorter than 350 nm which is biologically hazardous for the eye;

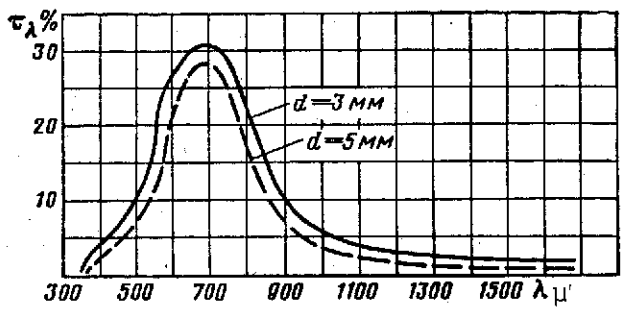


Figure 5.39. Spectral characteristic of smoked glass light filter [15].
d — light filter thickness; τ_λ — light transmission coefficient; λ — wavelength.

— limit the magnitude of the light flux in the visible and IR parts of the spectrum to 5 — 10%, considering the danger of the effect of the high thermal flux created by these parts of the spectrum on man's face and head. If we assume that the solar constant is 1200 kcal/m^2/h, then if the filter transmits 10% the thermal flux is reduced to 120 kcal/m^2/h, which is considered allowable for the human eye.

In selecting the material for the light filter, we must consider the fact that its surface temperature may vary over a wide range. /164

In order to reduce the thermal flux passing through the glass, we should attempt to minimize — at the external light filter — the ratio of the solar energy absorption coefficient A_s to the emissivity ε_0.

The stated requirements can be satisfied by light filters which use as the light filtering layer thin films of metals which have high solar energy absorption coefficient. Such metals are Ag, Au, Cu, Al. However, since the silver and copper

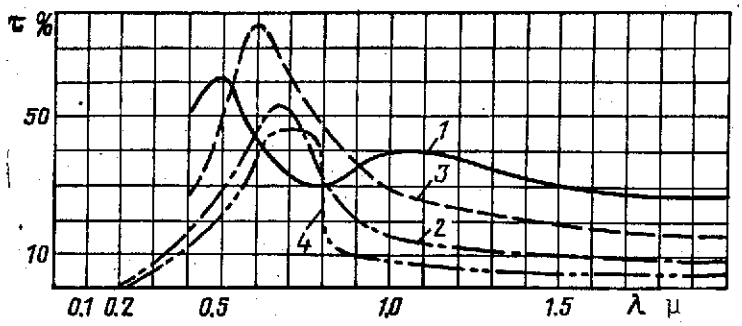


Figure 5.40. Typical spectral characteristics of coatings on quartz substrate [16].

1 — aluminum coating; 2 — gold coating on nickel oxide substrate (Ni_2O_3 + Au + Ni_2O_3); 3 — gold coating on bismuth oxide substrate (Bi_2O_3 + Au + Bi_2O_3); 4 — gold coating on lead oxide substrate (PbO + Au + PbO).

films are not sufficiently stable, gold films are usually used.

Since the gold coatings have poor adhesion (bonding) with glass, a sublayer of certain metal oxides is first applied to the glass surface and then the main (gold) layer and a protective layer of the same material as the sublayer (Ni_2O_3, Bi_2O_3, and others) are applied.

Typical spectral characteristics of such a light filter are shown in Figure 5.40.

The light filtering coating may be applied to the inside surface of the glass to protect the coating against mechanical damage.

4. Outer Garments

The outer garment, which is worn over the emergency-survival pressure suit, is intended to:

— protect the suit shell against mechanical damage in the flight vehicle cabin after landing or in case of emergency egress from the cabin;

— provide attachment and storage for the required emergency-survival equipment, documents, and other flight equipment articles.

The following requirements are established for the fabrics from which the outer garment is made:

— resistance to tearing forces no less than 10 — 15 kG;

— breaking load 150 — 200 kG (for strip 5 cm wide);

— fabric weight no more than 200 — 300 G/m^2;

— inflammability.

Moreover, the fabric must have sufficiently attractive external appearance and permit dyeing (in white, orange, and protective colors). /165

The outer garment is made in coverall form (Figure 5.41). It should be easy to remove and provide the possibility for use of all the articles and equipment located on the garment. The garment color is selected as a function of pressure suit application. For example, suits intended for overwater flights are colored bright orange. This color is easily seen on the surface of the ocean.

Glass fiber fabric may be used as the inflammable material. Polyester fiber fabrics do not support combustion and extinguish themselves upon removal of the combustion source. One drawback of these fabrics is their low melting point (at temperatures above 200 — 250° C, they lose their strength completely and break down — they melt).

Figure 5.41. Outer garment for pressure suit of cosmonaut Yu. A. Gagarin.

1 — air fill hose for flotation collar; 2 — communications radio; 3 — signal pistol with cartridges; 4 — hose for oxygen supply to helmet; 5 — single-point connector for hoses supplying air to the suit.

About four square meters of fabric are required to make the outer garment, which weighs 1 — 1.5 kG.

5. Ventilating Garment

The ventilating garment forms a part of the pressure suit and provides ventilation of the space under the suit and removal of the moisture and other products released by the human organism. The air supplied to the garment also aids in maintaining the wearer's body temperature.

In the high ambient air temperature case, ventilation of the pressure suit with cold air provides evaporation of the moisture (sweat) released by the organism and thereby provides body cooling. At ambient temperatures below freezing, ventilation of the suit by warm air protects the organism against chilling.

The ventilating garment must satisfy the following basic requirements:

— provide evaporation of the moisture released by the organism;

— protect the individual against overheating and chilling;

— have low hydraulic resistance.

The air enters the garment through sealed inlet fittings and is directed to various parts of the body by means of a distributor. The air circulating in the garment absorbs the heat, evaporated perspiration, and gaseous emissions of the human organism. The space (ventilation gap) in which the ventilating air travels is bounded on the one side by the

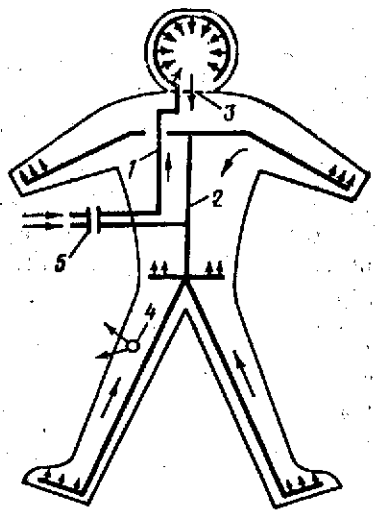


Figure 5.42. Split suit ventilation system.

1 — breathing oxygen supply hose; 2 — ventilation line; 3 — separator; 4 — air discharge to outside (through pressure regulator); 5 — single point hose connector.

hermetic pressure suit shell and on the other side by the body surface.

Split or *common* ventilation systems can be used in pressure suits.

In the split ventilation system, oxygen is usually suppled to the helmet for breathing, while the torso is ventilated by air or some other inert gas (Figure 5.42).

In the common ventilation /166
system, the gases supplied enter beneath the pressure suit shell through a single inlet port. The following construction variants of these systems are known (Figure 5.43):

— with air (oxygen) supply to the helmet and torso (see Figure 5.43a);

— with air supply to the torso and limbs and discharge from the helmet (see Figure 5.43b);

— with air supply to the helmet and discharge from the torso and limbs by means of tubes (see Figure 5.43c).

With regard to technique for distributing the air in the pressure suit, these systems may be subdivided into the *hose*, *panel*, and *combined* types.

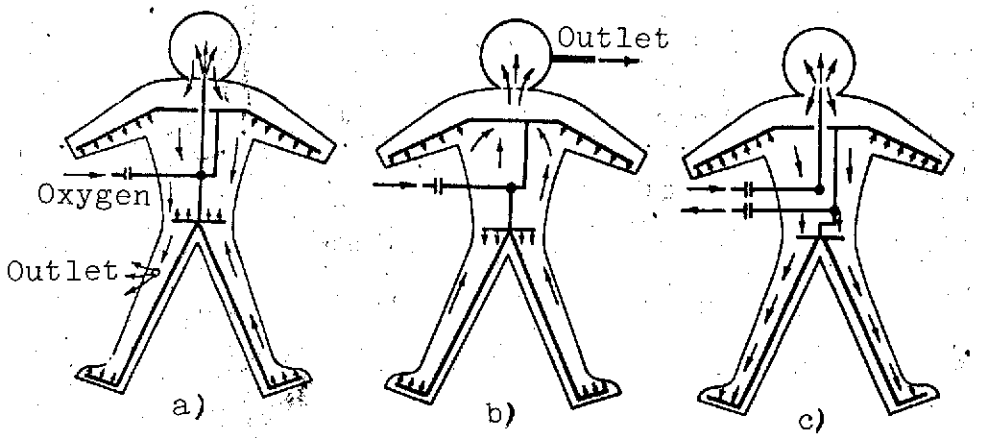


Figure 5.43. Suit ventilation schemes [1].
a — with air (oxygen) flow to helmet and trunk; b — with air flow to trunk and extremities and discharge from helmet; c — with air flow to helmet and discharge from trunk and extremities.

In the hose type ventilation system, the air is supplied through flexible hoses of invariable inside diameter to the various regions of the body surface (Figure 5.44).

In the panel type ventilation system, the ventilating garment is made in coverall form with two airtight shells (Figure 5.45).

The operating principle of this system is clarified in Figure 5.46. The air supplied to the garment enters the space between the two shells 1 and 2. Discharge of the air from this space to the individual's body is accomplished through the small holes 5 in the inner shell 2. The used air is discharged from beneath the garment through the large holes 4.

The garment shown in Figure 5.47 with combined type ventilation system consists of a coverall, collector, system of hoses and panels. The coverall is made from a lightweight but sufficiently strong fabric and serves as a foundation to which

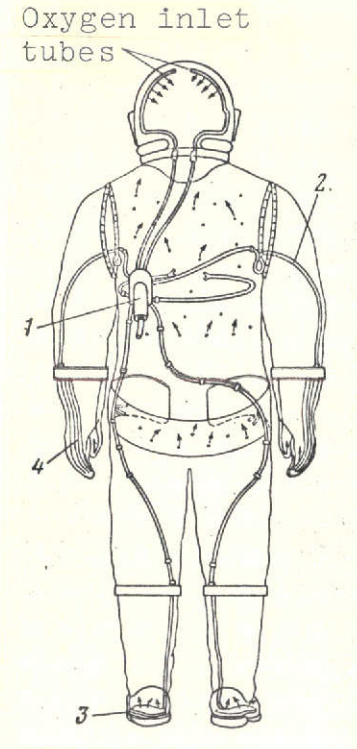


Figure 5.44. Ventilation garment of pressure suit with hose type ventilation system.

1 — air inlet manifold; 2 — ventilation system hose; 3 — ventilated inner soles; 4 — glove ventilation tubes.

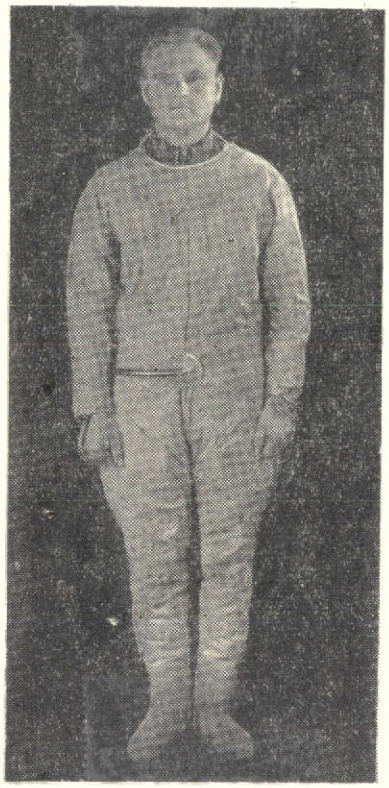


Figure 5.45. Ventilation garment of pressure suit with panel type ventilation system [2].

the entire ventilating system is attached. The collector is intended for reception of the air supplied to the garment and its further distribution to all parts of the body.

Reinforced rubber and plastic hoses with internal diameter 8 — 12 mm and also hoses of hermetic fabric with internal wire stiffening spirals are used for the ventilating system.

The ventilation system resistance depends on the ventilating air flowrate and the hose inside section dimensions and usually does not exceed 200 — 300 mm Hg for an air flowrate of

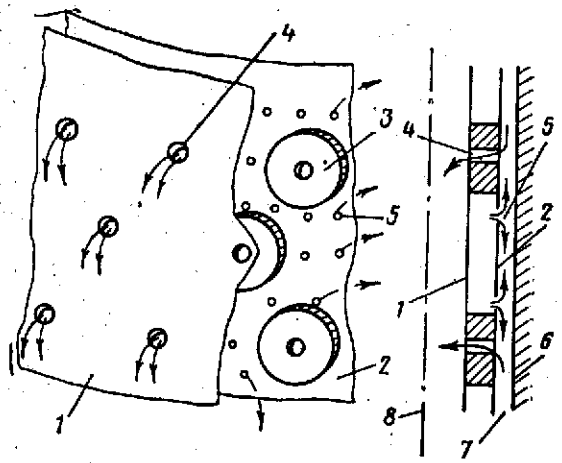


Figure 5.46. Portion of ventilated garment panel of pressure suit with panel type ventilation system.

1 — outer shell; 2 — inner (near the body) shell; 3 — spacer (washer); 4 — air discharge port; 5 — holes in inner shell for air discharge; 6 — surface of wearer's body; 7 — ventilation gap; 8 — pressure suit hermetic shell.

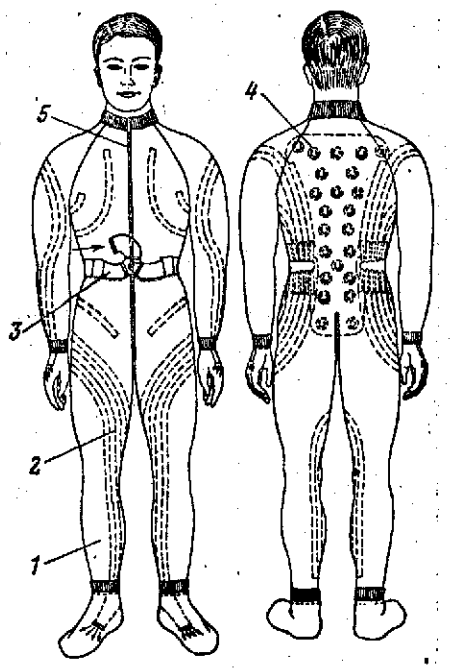


Figure 5.47. Ventilation garment of pressure suit with combined (hose and panel) ventilation system.

1 — coverall-ventilation garment; 2 — ventilation hoses; 3 — air inlet manifold; 4 — back ventilation panels; 5 — zipper.

300 liters(s)/minute. The ventilating air flowrate usually varies in the range from 50 to 300 liters(s)/minute. With an air flowrate of less than 50 liters(s)/minute, it is not possible to completely remove the /168 moisture released by the individual from the pressure suit. The temperature of the air supplied to the pressure suit may vary as a function of ambient conditions in the range from 10 to 80° C; local body burning (at locations where the air is discharged against the body) may occur at air temperatures above 80° C. Air temperatures below -5° C may lead to overcooling of the individual in the pressure suit.

TABLE 5.5

APPROXIMATE DATA ON RATIONAL AIR DISTRIBUTION IN PRESSURE SUIT VENTILATING GARMENT

Part of man's body to which air is supplied	Air quantity %	Part of man's body to which air is supplied	Air quantity %
Arms	20	Lower back	5
Chest	5	Hips	10
Abdomen	5	Knee	5
Back	15	Sole of foot	35

Approximate data on rational air distribution in the ventilating garment are presented in Table 5.5.

The amount of heat which must be removed by the ventilating garment air is

$$Q = Q_{es} + Q_{ma} \tag{5.18}$$

where Q_{es} is the heat expended in evaporating sweat; Q_{ma} — heat expended in heating the moist air flowing through the garment.

The first of these terms

$$Q_{es} = rG_s, \tag{5.19}$$

where r is the latent heat of vaporization; G_s — amount of moisture (sweat) removed from the garment in kG/hr.

The amount of heat which can be removed by the ventilating garment corresponds to the ventilating air enthalpy change.

The enthalpy of one cubic meter of moist air is made up of the dry air and vapor enthalpies

$$i_0 = \gamma_d ct + \gamma_v (597 + 0{,}45t). \qquad (5.20)$$

The enthalpy of one kilogram of moist air is

$$i_{ma} = \frac{i_0}{\gamma_0} = \frac{\gamma_d}{\gamma_0} ct + \frac{\gamma_v}{\gamma_0} (597 + 0{,}45t), \qquad (5.21)$$

where γ_d is the specific weight of dry air, γ_v — specific weight of vapor; c — weight specific heat of air, on the average equal to 0.24 kcal/kG/°C (at 0° C and 760 mm Hg); γ_0 — specific weight of the vapor-air mixture $\gamma_0 = \gamma_d + \gamma_v$. /169

The relationship between the specific weight of the vapor and the moisture content is expressed by the formula

$$\gamma_v = \gamma_0 \frac{d_v}{1 + d_v}.$$

The moisture content of the air is expressed in terms of the corresponding partial pressures p_v of the water vapor and p_a of the dry part of the ventilating air [10]:

$$d = 623 \frac{p_n}{p_n} \text{ g/kG} \qquad (5.22)$$

or

$$d = 623 \frac{p_n}{p_0 - p_n} \text{ g/kG}, \qquad (5.23)$$

where p_0 is the pressure or vapor pressure of the vapor air mixture (barometric pressure).

$p_0 = p_d + p_v$, where p_d is the partial pressure of the dry air, p_v — partial pressure of the water vapor.

After touchdown, forced supply of air into the garment is terminated.

6. Underwear

Underwear has a direct influence on the skin temperature of the individual, the temperature of the air layer adjacent to his skin, and on the functions performed by the skin — suppressing or stimulating these functions. Therefore, underwear properties become quite important.

Requirements based on the following considerations are imposed on underwear:

— the underwear must be sufficiently soft and elastic to avoid skin irritation;

— the materials used for underwear must restrict as little as possible the heat transfer and removal of carbon dioxide and moisture from the pressure suit;

— the materials must be hygroscopic, have good capability for absorbing skin emission products, and high vapor and air permeability in both dry and wet conditions.

Underwear must not stick to the skin in the wet state, so that it does not prevent the release and evaporation of perspiration. Fabrics with fleecy surface and suitable thread interweaving satisfy this requirement quite well. The surface of the underwear fabrics must be soft and smooth to avoid skin irritation.

The underwear must integrate well with the pressure suit construction.

Hygroscopicity of a fabric characterizes the ability of the material to absorb (sorb) water from the air in the form of water vapor and retain it under certain conditions.

Fabrics made from vegetable fibers absorb the moisture emitted by the body rapidly and transfer it rapidly to the external medium. Conversely, woolen fabrics absorb moisture slowly and transfer it slowly.

The degree of hygroscopicity of textile fabrics is characterized by the quantity of moisture present in the test specimen prior to and after drying, expressed by the weight change in percent of the initial weight. Underwear made from viscose knitwear and woolen knitwear has the highest hygroscopicity.

Fabric hygroscopicity is usually measured at 70 and 100% ambient air humidity. /170

The air permeability of a fabric characterizes its ability to pass air through itself. The air permeability depends on the pressure differential, therefore in order to obtain comparable results for various fabrics, it is usually determined with a pressure differential of 5 mm H_2O.

The degree of air permeability is measured in $cm^3/cm^2/sec$ (at standard conditions). Fabric air permeability facilitates normal gas exchange between the body and the surrounding air.

The vapor permeability defines the ability of a material to pass through itself water vapor from a medium with higher moisture content of the air into a medium with lower moisture content. Vapor permeability is measured by the amount of moisture in milligrams vaporized per hour per square centimeter

TABLE 5.6

HYGIENIC CHARACTERISTICS OF SOME UNDERWEAR FABRICS

Fabric	Hygroscopicity in weight/% for air humidity		Air permeability $cm^3/cm^2/sec$	Vapor permeability $mG/cm^2/h$	Water absorption g/h
	70%	100%			
Cotton knitwear	6.6	22	2.61	—	3.67
Cotton-linen knitwear	7.5	23	7	1.9	2.7
Linen knitwear	7	25	13	2	2.53
Wool knitwear	10	26	3.75	1.9	2.5
Viscose knitwear	4	36	1.46	1.81	4.65

of material. Inadequate vapor permeability leads to water vapor retention in the air layer beneath the underwear, i.e., moistening of the underwear, and this hinders sweat evaporation.

The water absorptivity (or water retaining capacity) characterizes the ability of the material to absorb water in the liquid state. The amount of water which can be retained by the test specimen when totally wetted is called the maximum water absorptivity. The relative water absorptivity is

$$B = \frac{G_W - G_0}{G_0} \cdot 100, \qquad (5.24)$$

where G_W is the weight of the wetted specimen; G_0 — specimen weight when dried to the original weight.

Data on the hygienic characteristics of some underwear fabrics are shown in Table 5.6.

Moreover, it should be considered that, in the course of a week, there is released from an individual's entire body surface from 100 to 300 g of skin fat, from 3 to 17 liters of perspiration (up to 35 — 40 liters in a hot climate) and from 40 to

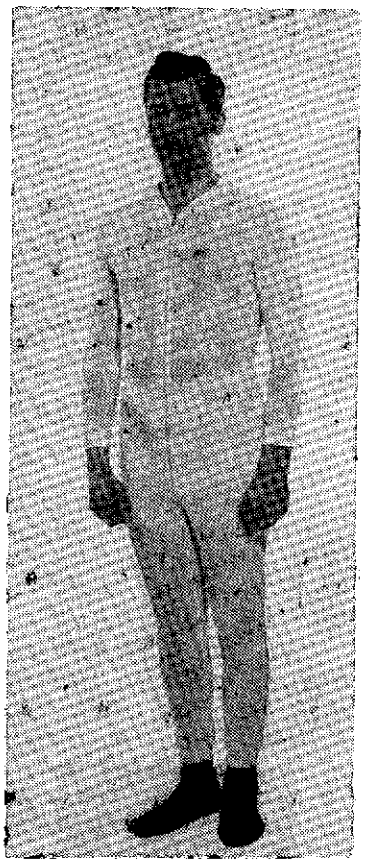


Figure 5.48. Pressure suit undergarment made in coverall form.

90 g of fine scales of the surface corneous layer of the skin [9]. The underwear removes these cutaneous emissions from the skin, and thus the air permeability of the contaminated underwear decreases by nearly 20%, its weight increases by 12%, and thickness increases by up to 28%.

Underwear is made in the form of shirts (sweaters) and pants or in the form of coveralls with opening in front (Figure 5.48).

Knitted fabric (cotton-linen or cotton) is usually used to make underwear. Warm winter underwear is made from knitted woolen fabric.

The physico-mechanical characteristics of some underwear fabrics are presented in Table 5.7.

Depending on the size and height of the individual for whom it is made, the weight of cotton underwear varies from 500 to 600 grams.

7. Thermal Protection Garment

In order to determine the properties which the thermal protection garment should have, it is necessary to establish approximately the most typical conditions which the flight vehicle crew may encounter during flight:

TABLE 5.7

PHYSICO-MECHANICAL CHARACTERISTICS OF UNDERWEAR MATERIALS

Material	Weight g/m^2	Lengthwise tensile strength, kG	Lengthwise elongation %	Thickness mm	Thermal conductivity kcal,m/hr/°C	Thermal resistance $m^2/hr/°C/kcal$
Cotton knitwear	135	23.4	90	0.85	—	—
Cotton-linen knitwear	175	25.0	74	0.65	0.085	0.008
Wool knitwear	335	32	96	1.25	0.08	0.015
Viscose knitwear	135	15.3	68	0.4	—	—

— on the ground awaiting flight under various climatic conditions (specifically, with ambient air temperature from -50 to +60° C);

— flight in pressurized or unpressurized flight vehicle cabin;

— parachute descent to the land under various climatic conditions;

— parachute descent to the water with water temperature near 0° C;

— emergency landing of the flight vehicle in the arctic region.

The temperature conditions in the unpressurized cabin may differ as a function of vehicle flight altitude and speed. At subsonic flight speeds in case of vehicle air conditioning system failure, the temperature in the cabin may descend to minus 20° C. If the flight speed is supersonic, the flight vehicle skin temperature rise may reach several hundred degrees and the temperature in the cabin may increase to 80° C.

The temperature conditions during parachute descent and the duration of their action can be judged by the temperature variation with altitude in the standard atmosphere (GOST 4401-64) and from the parachute descent characteristics shown in Figure 3.13. /172

In case of parachute descent into water having temperature 0 — 5° C indications of shock will appear in only a few minutes in individuals who have not received cold water survival training.

Thus, a difficult problem arises of protecting man in the course of flight from the effects of both low and high temperatures. This problem cannot be resolved simply by selection of the optimum thermal insulation of the clothing (pressure suit), since under certain conditions, the individual will be too hot and under others — too cold.

Experience in the use of pressure suits has shown that efficient thermal protection of man can be achieved with the aid of the thermal protection garment (TPG), which — along with the ventilating garment — forms part of the pressure suit system.

In case of low ambient medium temperatures, the TPG reduces the heat transfer from the pressure suit, while in case of high ambient temperatures, it reduces the heat influx from the outside to the degree that the ventilating garment located beneath the TPG can maintain an air temperature which provides normal thermal sensations and temperature regulation for the individual.

The thermal protection properties of clothing can be characterized by the magnitude of its *thermal resistance*, which is the ratio of the thermal conductivity (λ) to the thickness (δ) of the clothing packet and has dimensions $m^2/hr/°C/kcal$.

The thermal conductivity λ indicates the amount of heat which passes through one square meter of clothing one meter thick per hour with a temperature difference of one degree.

The reciprocal of λ/δ is called *the heat transfer coefficient.*

In some countries, a new unit of measurement has been introduced to characterize the magnitude of the thermal insulation: the clo, 1 clo = 0.18 $m^2/hr/°C/kcal$.

Clothing with thermal insulation of 1 clo provides comfort conditions for a man at rest (heat output of about 50 $kcal/m^2/hr$) with air temperature 21° C, relative humidity less than 50%, and air velocity no more than 0.1 m/s (see Chapter 2 of [19]).

Figure 5.49 shows a graph for calculating the thermal insulation of man's clothing necessary to provide normal conditions for an individual as a function of ambient air temperature and the amount of heat generated by the individual for various physical workloads.

The thermal protection garment is made in the form of a separately donned coverall or in the form of a thermal protection shell comprising an integral part of the pressure suit.

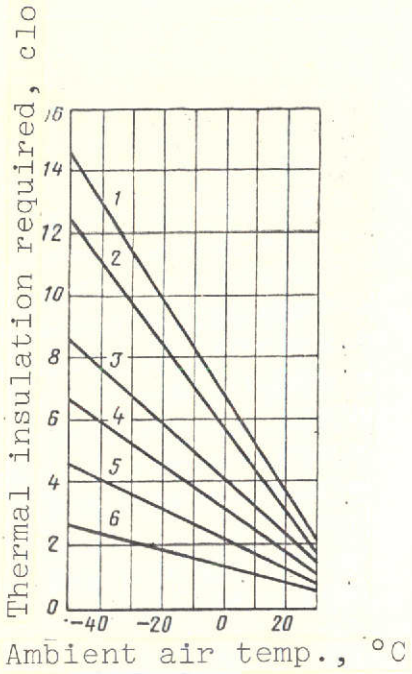


Figure 5.49. Thermal insulation necessary to ensure normal state of man [2].

1 — sleeping; 2 — resting; 3 — working (heat output 100 kcal/hr); 4 — working (heat output 150 kcal/hr); 5 — performing moderate work (210 kcal/hr); 6 — performing heavy work (heat output 420 kcal/hr).

Figure 5.50. Thermal protection garment made from knit wool fabric for pressure suit [2] (garment weight 1.8 kG, thermal resistance 0.15 m^2/hr/°C/kcal).

The coverall has a front opening for donning and doffing. The opening is usually closed by means of a zipper. Lightweight fabrics having comparatively high thermal resistance (wool, porolon, synthetic fibers) are used to /173 make the garment. Figure 5.50 shows a TPG made from wool tricotage.

The TPG for the pressure suit of cosmonaut Yu. A. Gagarin was made of porolon and knitted pure wool cloth (Figure 5.51). The porolon was covered on the inside and outside with the lightweight cloth. The ventilating system was sewn directly to the inner fabric (liner) of the TPG. The garment can be used as an outer garment without the pressure suit.

Figure 5.51. Thermal protection garment made from porolon and knit wool fabric for pressure suit of Yu. A. Gagarin (garment weight 3.2 kG: two silk shells weighing 0.3 kG, 12 mm thick porolon weighing 0.4 kG, 5.0 mm thick knit wool fabric weighing 1.5 kG, ventilation system weighs 1 kG, thermal resistance is 0.4 $m^2/hr/°C/kcal$).

The TPG, when it is at the same time the hermetic shell, can be made from foam rubber with closed pores. This rubber is very light in weight. Its main drawbacks are comparatively poor strength and flammability characteristics.

The thermal resistance of the pressure suit is determined by the overall thermal protective properties of the entire packet.

The process of heat transfer from an individual dressed in a pressure suit to the surrounding medium has not yet received adequate study, and therefore simplifications are used in calculations.

In view of the complexity of the human body geometric forms, in heat transfer calculations the pressure suit is replaced by a system of cylindrical shells. The magnitudes of the ventilation gaps in the sections being examined are assumed to be constant, and the heat capacity of the pressure suit itself is not considered.

Depending on the design case, we usually specify:

— thermal resistance of the individual pressure suit elements;

— dimension of the ventilation gap;

— velocity of the air (oxygen) in the ventilation gap;

— temperature and velocity of the outside air;

— temperature of the ventilating air at the pressure suit inlet and outlet (t_{in} and t_{out}).

The overall thermal resistance of the pressure suit is evaluated by the combined insulating effect of the entire system and for the configuration shown in Figure 5.52 is determined by the:

— thermal resistance of the underwear for the temperature head $t_I - t_{II}$;

— amount of heat removed by the ventilating air from surface 2;

— heat transferred from underwear surface to TPG surface by radiation; /174

— heat transferred by ventilating air to TPG surface;

— thermal resistance of TPG with temperature head $t_{III} - t_{IV}$;

— thermal resistance of helmet shell with temperature head $t_{IV} - t_V$;

— thermal resistance of restraint shell with temperature head $t_V - t_{VI}$;

— thermal resistance of outer garment with temperature head $t_{VI} - t_{VII}$;

— thermal resistance to heat transfer from outer surface to surrounding air (heat transfer resistance); this causes the temperature differential $t_{VII} - t_{VIII}$.

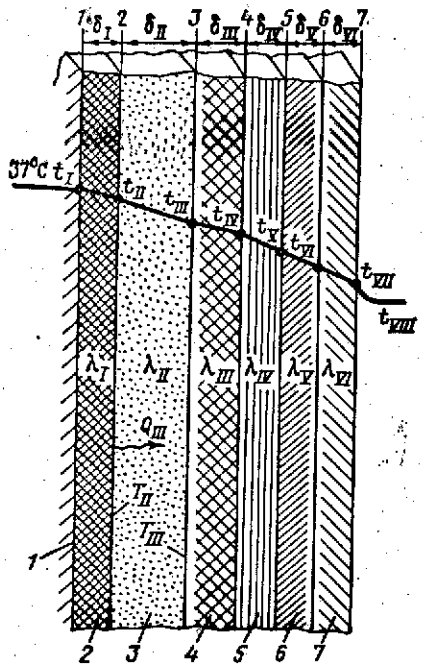


Figure 5.52. Illustration for calculating heat transfer from multilayer pressure suit to ambient medium. 1 — man's body; 2 — underclothing; 3 — ventilation gap; 4 — thermal protection garment (TPG); 5 — hermetic shell; 6 — restraint shell; 7 — outer garment; δ — layer thickness; λ — thermal conductivity; t_I — t_{VIII} — surface temperature in °C; t_{II} — t_{III} — surface temperature in °K; Q_3 — radiative thermal flux.

It is obvious that heat exchange between the man's body and the adjacent undergarment takes place with different positions of the undergarment in relation to the body surface. The underwear may fit tight against the body or there may be an air space of definite thickness between the underwear and the body. In calculations, it is usually assumed that the heat transfer between the body and underwear is accomplished by convection.

The amount of heat transferred by the human body through the underwear is (see Figure 5.52)

$$Q_1=\frac{\lambda_1}{\delta_1}(t_1-t_{11})S\tau, \qquad (5.25)$$

where S is the surface area of man's body, τ — time during which heat transfer takes place.

We obtain from (5.25) the specific thermal flux

$$q_1=\frac{\lambda_I}{\delta_I}(t_1-t_{11}) \text{ kcal/m}^2\text{/hr}. \qquad (5.26)$$

We can obtain from (5.26)

$$q_1 = \frac{(t_I - t_{II})}{\delta_I/\lambda_I} \text{ kcal/m}^2\text{/hr}. \qquad (5.27)$$

Consequently, the heat flux q_1 is directly proportional to the temperature head and inversely proportional to the thermal resistance.

The surface temperature t_{II} can be found from the expression

$$t_{II} = t_I - \frac{\delta_I}{\lambda_I} q.$$

The amount of heat removed by the ventilating air as a result of convective heat exchange between the air and the underwear surface per unit time is /175

$$Q_{2air} = \alpha_{con} (t_{II} - t^{II}) S\tau, \qquad (5.28)$$

where α_{con} is the coefficient of convective heat transfer from the underwear surface to the ventilating air, t^{II} — the air temperature in the pressure suit in ° C.

It follows from (5.28) that the specific heat flux

$$q = \alpha_{con} (t_{II} - t^{II}). \qquad (5.29)$$

In calculating the amount of heat given up by the body by means of convection, the greatest difficulty lies in determining the coefficient α_{con}, since its magnitude is not constant and depends on the temperature, pressure, and velocity of the air, the body surface form and dimensions, and the surface condition. Account for all these factors is very complex.

With accuracy adequate for practical calculations, these solutions are approximated by comparatively simple computational formulas which are presented in the corresponding handbooks [11].

It has been established experimentally that the air flow through the ventilation gaps should be laminar in order to reduce the air head losses and improve the heat transfer.

The Reynolds number, which defines the nature of the gas flow through the gap, is

$$\mathrm{Re}=\frac{v2\delta}{\nu}, \qquad (5.30)$$

where δ is the ventilation gap width in m, v — the air velocity in the ventilation gap in m/sec, ν — the kinematic viscosity in m^2/sec.

Considering that $S\Pi\delta$ (here Π is the average wetted perimeter of the flow section), we obtain

$$\mathrm{Re}=\frac{2G}{\Pi\nu_T}. \qquad (5.31)$$

Taking the critical value Re_{cr} = 1000 — 1600, defining laminar flow, we can determine from (5.31) the ventilation gap dimensions for which the air flow in the gap will be laminar.

Example. Let us determine the Reynolds number for the following conditions.

The temperature of the air ventilating the pressure suit is 20° C. The pressure suit perimeter in the chest region is Π_o = 1.11 m. The perimeter (circumference) of the wearer's chest is 0.96 m.

Q = 0.4 m^3/min is the air flowrate.

$\nu = 15 \cdot 10^{-6}$ m^2/sec (see Table 4.7).

The air velocity in the ventilation gap

$$v = \frac{Q}{S} = \frac{2Q}{(\Pi_i + \Pi_o)\delta} = \frac{2 \cdot 04}{(1.11 + 0.96) \cdot 0.046} = 0.02 \text{ m/s}$$

where

$$\delta = \frac{D_o - D_i}{2} = \frac{0.35 - 0.304}{2} = 0.023 \text{ m};$$

$$\text{Re} = \frac{v2\delta}{\nu} = \frac{0.02 \cdot 2 \cdot 0.023 \cdot 10^6}{15} = 61.$$

We see that the air flow is laminar.

The amount of heat generated by the ventilating air at the TPG surface by convective heat transfer is /176

$$Q_{\text{air}} = \alpha_{\text{con}} (t^{II} - t_{III}) S\tau. \qquad (5.32)$$

The radiative thermal flux from the underwear surface to the TPG surface as a process of radiative heat transfer between two parallel walls is found from the well-known formula

$$Q_s = \sigma_0 = \varepsilon_{ef} S (T_1^4 - T_{III}^4), \qquad (5.33)$$

where σ_0 is the blackbody radiation constant, S — the surface area ($S = S_{II} = S_{III}$); T_{II} and T_{III} — the temperatures at surfaces 2 and 3, ε_{ef} is the effective surface emissivity in the case of heat transfer between two surfaces located one inside the other

$$\varepsilon_{ef} = \frac{1}{1/\varepsilon_2 + S_I/S_{II}(1/\varepsilon_3 - 1)}, \qquad (5.34)$$

where ε_2 and ε_3 are the emissivities of surfaces 2 and 3.

The amount of heat transmitted through the TPG (temperature head $t_{III} - t_{IV}$), hermetic shell (temperature head $t_{IV} - t_V$), restraint shell (temperature head $t_V - t_{VI}$), and outer garment (temperature head $t_{VI} - t_{VII}$) is calculated using (5.25).

Heat exchange between the outer surface of the pressure suit and the surrounding medium is accomplished as a result of convective heat transfer and radiation. The overall heat transfer coefficient α in this case can be represented as

$$\alpha = \alpha_{con} + \alpha_r, \qquad (5.35)$$

where α_{con} is the convective heat transfer coefficient, α_r — radiative heat transfer coefficient.

Formula (5.32) can be used to determine α_{con}.

The coefficient α_r can be found from the formula

$$\alpha_r \approx 0.04\,\varepsilon_{ef}\,\sigma_0\left(\frac{T_m}{100}\right)^3, \qquad (5.36)$$

where $T_m = (T_1 - T_2)/2$, here T_1 is the temperature of the pressure suit outer surface, T_2 — temperature of the pressurized cabin walls, ε_{ef} — effective emissivity of the pressure suit determined from (5.34).

The overall thermal resistance R_{ov} of the pressure suit can be represented by the sum of the thermal resistances

$$R_{ov} = R_p + R_s, \tag{5.37}$$

where R_p is the thermal resistance of the pressure suit packet, and R_s — thermal resistance of the outer surface of the pressure suit.

It is obvious that the overall specific heat transfer through the pressure suit is

$$q = \frac{\Delta t}{R_{ov}}, \tag{5.38}$$

where Δt is the overall temperature differential.

Heat transfer with man in the water. In the course of a short time, the outer surface of the pressure suit takes on the temperature of the water.

If we take the temperature head from Figure 5.53 and the heat release of a man floating in water to be on the average 100 kcal/m^2/hr, then according to (5.38), the pressure suit will /177 have the overall thermal resistance R_{ov} = 0.34 m^2/hr/°C/kcal.

When the pressure suit is in the water, it is compressed and its ventilation gap decreases and actually does not increase the thermal resistance of the pressure suit. Therefore, in this case, the overall heat transfer of the pressure suit will be determined (see Figure 5.53) only by the thermal resistance of the underwear, the TPG, and the hermetic shell (the restraint shell and the outer garment have no influence on the thermal protection of the individual since they become wet in the water),

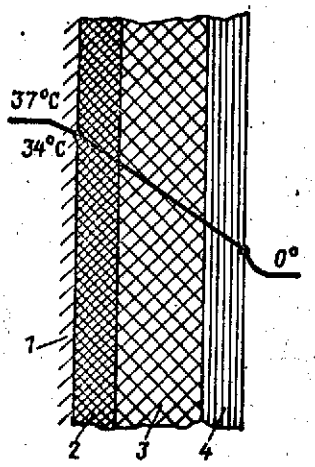


Figure 5.53. Diagram of temperature head with man floating in pressure suit.

1 — man's body; 2 — underwear; 3 — thermal protection garment; 4 — hermetic shell.

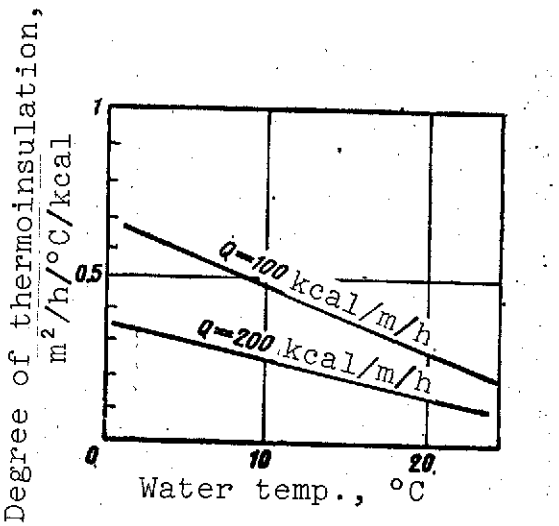


Figure 5.54. Calculated data on thermal insulation required for man submersed in water.

i.e., $R_{ov} = R_u + R_{TPG} + R_{hs}$.

If we assume that the thermal resistance of cotton underwear $R_u = 0.03$ m²/hr/°C/kcal and $R_{hs} = 0.025$ m²/hr/°C/kcal, then in the considered example, $R_{TPG} = 0.285$ m²/hr/°C/kcal.

Figure 5.54 shows calculated data on the thermal insulation required for exposure in water as a function of the individual's heat output level and water temperature.

When the ambient medium temperature is higher than man's body temperature, heat is transferred from the surrounding medium to the man in the spacesuit (Figure 5.55). In this case, the heat is removed solely by ventilation of the pressure suit by the cooling air, and the heat balance equation can be written in the form: $Q_{air} = Q_{man} + Q_{out}$, where Q_{man} and Q_{out} are the amounts of heat released by the man and supplied to him from outside.

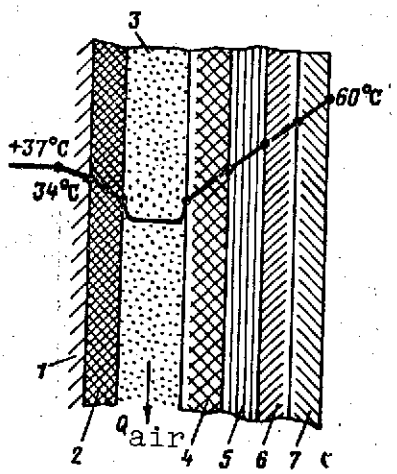


Figure 5.55. Illustration of temperature head in pressure suit with ambient temperature higher than man's body temperature.

1 — man's body; 2 — underwear; 3 — ventilation gap; 4 — thermal protection garment; 5 — hermetic shell; 6 — restraint shell; 7 — outer garment.

If we assume that 200 kcal/hr of heat is removed by ventilating the pressure suit with air (Q_{air}) and that the heat production of the man (Q_{man}) is 100 kcal/m^2/hr, then it is obvious that the heat Q_{out} must not exceed 100 kcal/hr (or 50 kcal/m^2/hr). In this case, the thermal resistance of the pressure suit (for the values shown in Figure 5.55) is

$$R_{ov} = \frac{\Delta t}{q} = \frac{60-34}{50} = 0.56 \text{ m}^2/\text{hr}/^\circ\text{C}/\text{kcal}.$$

8. Gloves

Gloves are used to protect the hands against the action of low pressure (vacuum) and against chilling or overheating.

Under the action of cold on the human body, chilling of /179
the extremities occurs first of all. This is explained by the less intense blood circulation in the extremities and also by the relatively high heat transfer surface area of the arms and legs in comparison with their mass. The problem of thermal protection of the hands becomes particularly critical in the case of cabin depressurization and cooling down. Gloves must meet the following requirements:

— least possible restriction to mobility of fingers and wrist;

— ventilation of the gloves (to warm the hands, remove moisture released by the skin);

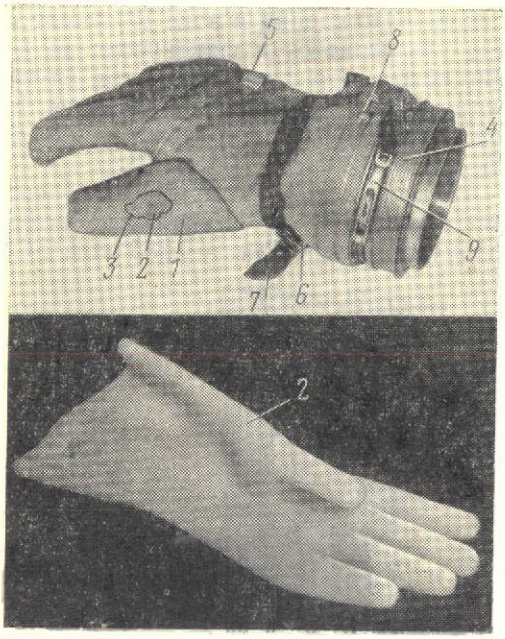


Figure 5.56. Pressure suit glove.

1 — restraint shell; 2 — hermetic insert; 3 — wool insert; 4 — split ring; 5 — restraint ring; 6 — tension strap buckle; 7 — tension strap; 8 — glove attach cable; 9 — lock latch.

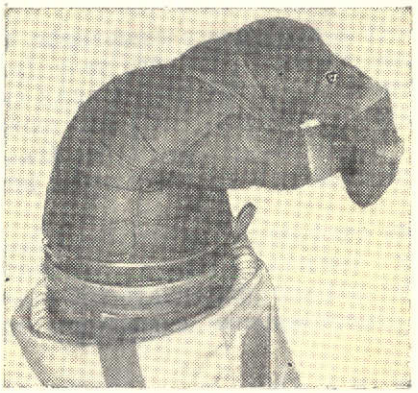


Figure 5.57. Glove providing good mobility of fingers and wrist.

— capability of donning and doffing;

— mechanical damage to the gloves must not lead to decrease of the differential pressure in the pressure suit.

A significant drawback of conventional gloves is their poor thermal protection properties in case of extended exposure of the wearer to low temperatures. The reason is that improvement of the protective properties by increasing the thermal insulation thickness hinders movement of the fingers and increases the heat transfer surface area.

Protection of the fingers against overcooling by means of mitteens is not acceptable because of the impossibility of working the individual fingers. A rational solution of this problem is to provide forced ventilation of the gloves using warm air.

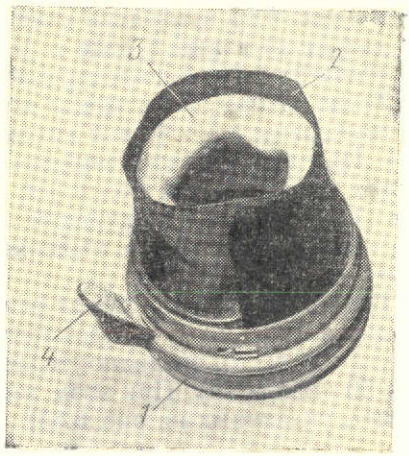


Figure 5.58. Cuff.

1 — split ring; 2 — restraint shell (rubberized fabric); 3 — rubber ring; 4 — strap for opening lock (removing cuff).

Figure 5.56 shows a pressure suit glove.

The restraint ring 5 prevents ballooning of the glove under the influence of differential pressure. After donning the glove, the connector mounted on the pressure suit sleeve latches automatically. To remove the glove, the lock hatch 9 must be opened.

A glove which provides greater mobility of the fingers and wrist is shown in Figure 5.57. Its outer restraint shell is made of kapron. Stretchable fabric inserts ("orange peels") are provided to improve finger mobility. The glove is attached by means of the ring 9 and the connector is sealed by the rubber flapper valve 10 (see Figure 5.27).

Cuffs are worn (Figure 5.58) to prevent air leakage from the pressure suit in case of glove failure. In case of glove damage, the differential pressure squeezes the inner rubber ring 3 of the cuff around the wrist and thereby prevents air leakage from the pressure suit. The cuff is easily removed. It is made in several sizes. With the cuff in place, the glove can be removed without any danger of suit depressurization.

To prevent sweating of the fingers, the gloves are ventilated by air coming from the pressure suit ventilation system. Figure 5.59 shows the construction of a glove with finger ventilation. The air is supplied to each finger as shown in Figure 5.44.

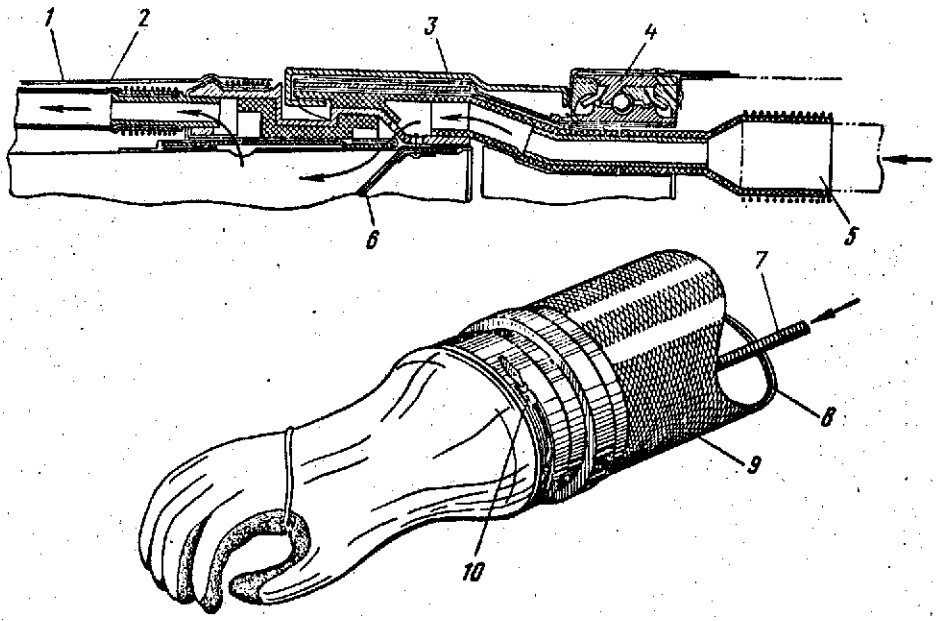


Figure 5.59. Glove with finger ventilation.

1 — glove shell; 2 — air supply to finger; 3 — outer ring; 4 — hermetic (wrist) bearing; 5 — air supply; 6 — cuff; 7 — ventilating system tube; 8 — suit shell; 9 — outer garment; 10 — glove lock.

The gloves are made in several sizes, determined by the circumference of the palm of the hand (in centimeters) divided by the glove measurement unit 2.67.

9. Pressure Suit Footwear

Footwear is used to protect the feet against mechanical damage, chilling and overheating, the effects of dampness and other external factors.

Footwear must conform to the shape of the foot and must be free (must not cause deformation of the foot, must not interfere with leg movement, must not create local pressures on the skin, blood vessels, or nerves). Footwear should be convenient, rapidly and easily put on and taken off, have low weight and small size, and remain securely on the foot.

Footwear for pressure suits is made in the form of: /181

— nonremovable hermetic boots which are integrated with the pressure suit shell;

— removable hermetic boots;

— nonhermetic overshoes or boots which are put on over the pressure suit shell.

In Soviet practice, nonremovable hermetic boots were used in the pressure suit of cosmonaut A. A. Leonov. They were made from the same fabric as the pressure suit restraint shell and foam rubber with closed pores was used as the sealing layer and insulation.

The removable hermetic boot shown in Figure 5.60 is made of leather and sealed by rubberized fabric. The boot terminates in a split ring and therefore is easily taken off and put on.

The removable overshoes are made from rubber or leather. Figure 5.61 shows the removable overshoes for the pressure suit of cosmonaut Yu. A. Gagarin. The upper part of the overshoe is made of leather and the sole is made of lightweight microporous rubber (overshoe weight 0.8 kG).

Of all the known types of flight footwear, fur flying boots and leather boots with fur lining have the best thermal insulation capability.

A major drawback of the fur boots is their weight (3 kG) and a rapid water absorption.

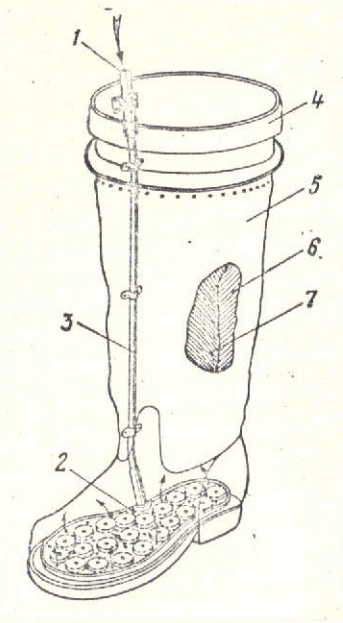


Figure 5.60. Removable hermetic boot for pressure suit [2].

1 — ventilation tube fitting; 2 — ventilated innersole; 3 — air supply tube; 4 — split ring; 5 — leather upper; 6 — leather liner; 7 — rubberized fabric sealing layer.

Figure 5.61. Removable boots for cosmonaut pressure suit [2].

The overall thermal resistance of fur boots whose uppers are made from two layers of fur and the sole from leather with thick (20 — 25 mm) felt inserts amounts to 0.5 $m^2/hr/°C/kcal$.

Fur stockings or woolen socks are often used to increase the thermal protection properties of flight footwear. Table 5.8 shows data on the thermal protection properties of various leg and foot insulations and Table 5.9 shows the characteristics thermal protection properties of various footwear types [12].

10. Pressure Suit Instruments

The pressure regulator in the pressure suit performs the following functions:

TABLE 5.8

THERMAL PROTECTION PROPERTIES OF VARIOUS LEG AND FOOT INSULATIONS [12]

Insulation type	Thickness mm	Thermoprotective property indexes	
		Thermal resistance $m^2/hr/°C/kcal$	in clo units
Sheep's wool stockings	10	0.3	1.67
Plush-weave wool stockings	4.2	0.12	0.66
Fine-weave wool stockings	1.5	0.04	0.22
Cotton flannelette foot wrappers (2 layers)	4.2	0.08	0.44

TABLE 5.9

THERMAL PROTECTION PROPERTIES OF FOOTWEAR [12]

Footwear type and construction	Weight per pair, g	Thermoprotective property indexes	
		Overall thermal resistance $m^2/hr/°C/kcal$	in clo units
Chrome leather boots, leather sole (cotton innersole)	860	0.22 — 0.24	1.22 — 1.34
Leather shoes, fur lined	2700	0.32	1.78
Leather shoes, leather sole	1900	0.24	1.34
Flight boots, two fur layers, sole 25 mm thick felt	3000	0.45 — 0.54	2.5 — 3
Fabric boots with galoshes	2200	0.29	1.6
Fabric boots without galoshes	1400	0.27	1.5
Conventional fabric boots	1600	0.32	1.78
PPS* boots	1600	0.24	1.34
PPS boots with plush weave wool socks	—	0.33	1.82

*Partial pressure suit (PPS).

— automatic maintenance in the suit of the specified differential pressure at all altitudes; /182

— discharge of air from the suit in case of excessive pressure increase;

— manual creation on the ground (or in flight) of differential pressure in the suit.

The following requirements are usually imposed on the pressure regulators:

— automatic maintenance of the differential pressure in the suit within given limits, regulation of the rate of pressure change in accordance with the minimum and maximum rate of air flow through it;

— high operational reliability and production simplicity;

— lowest possible degree of regulation nonuniformity.

In order to meet the posed requirements, absolute pressure regulators and combined absolute and differential pressure regulators are used in pressure suits.

A schematic of an absolute pressure regulator is shown in Figure 5.62. Here the sensing element is an evacuated bellows which is subjected to the pressure in the suit.

On the ground and during flight in a pressurized cabin, the valves 1 and 2 are open, and as air is supplied to the suit, a small differential pressure ($\Delta p = 0.02$ kG/cm^2), necessary to straighten out the suit shell and establish the ventilation gaps in the ventilating garment, will be maintained in the suit. In this case, the absolute pressure in the suit is close in magnitude

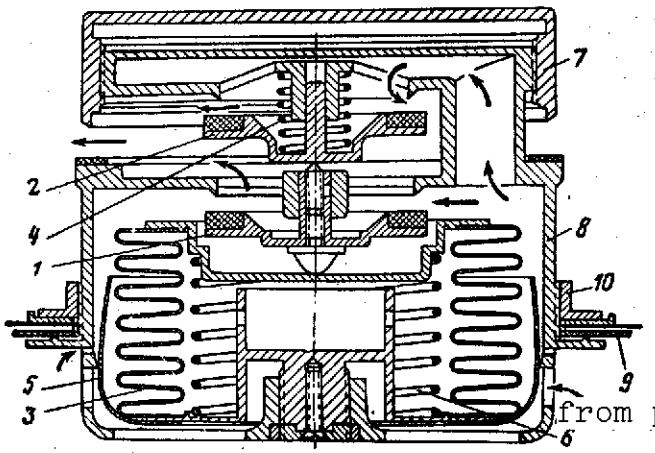


Figure 5.62. Pressure regulator in pressure suit with bellows. 1, 2 — valves; 3 — bellows; 4 — valve spring; 5 — rubber valve; 6 — bellows spring; 7 — valve cover; 8 — body; 9 — pressure suit shell; 10 — clamping nut.

to the pressure in the cabin and the evacuated bellows 3 exposed /183 to the action of this pressure is compressed.

As the absolute pressure in the cabin and in the pressure suit decreases, the bellows 3 is extended by means of the spring 6 and, overcoming the resistance of the spring 4, brings the valves 1 and 2 closer to their seats.

The air flowrate through the valves 1 and 2 will not change until the gaps between the seats and the valves decrease to a given value.

When the specified "altitude" in the cabin (and in the pressure suit) is reached, the bellows is stretched to the degree that change of the clearances between the seat and the valve begins to influence the air flowrate, and only then does the absolute pressure regulator come into play. Now, if the absolute pressure in the pressure suit becomes less than the specified value, the bellows stretches even more, closes the valves still

further, and reduces the air flowrate through them, as a consequence of which the pressure in the pressure suit increases to the established value. Conversely, with increase of the pressure in the suit the valve opening increases and the pressure decreases.

The differential pressure in the pressure suit is determined by the difference $\Delta p_{su} = p_{su \cdot abs} - p_{cab}$.

Air discharge from the pressure suit can be terminated completely and differential pressure created in the suit by rotating the cover 7.

For safety reasons, the described regulator is usually used together with an additional safety valve on the pressure suit shell.

The rubber check valve 5 is provided to prevent the possibility of water getting into the pressure suit through the regulator (when in the water).

Figure 5.63 shows a typical pressure regulator characteristic for different air flowrates.

A schematic of a combined pressure regulator is shown in Figure 5.64.

The regulator consists of two units: absolute and differential pressure controllers. Upon reduction of the outside pressure, the absolute pressure unit consisting of the aneroid stack 3, valve 2, and spring 7 begins to operate. As a result of expansion of the aneroid stack, subject to outside pressure, /184
this unit begins to gradually close the valve 2 and thereby maintains a constant absolute pressure in the pressure suit.

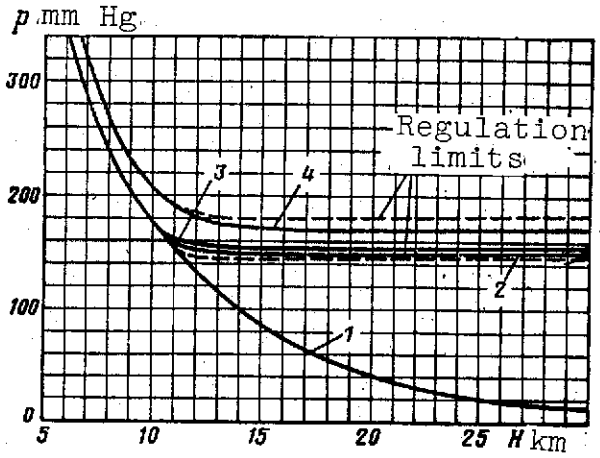


Figure 5.63. Possible characteristic of aircraft emergency-survival pressure suit pressure regulator.

1 — standard atmosphere; 2 — with 50 liters/minute flowrate; 3 — with 100 liters/minute flowrate; 4 — with 200 liters/minute flowrate.

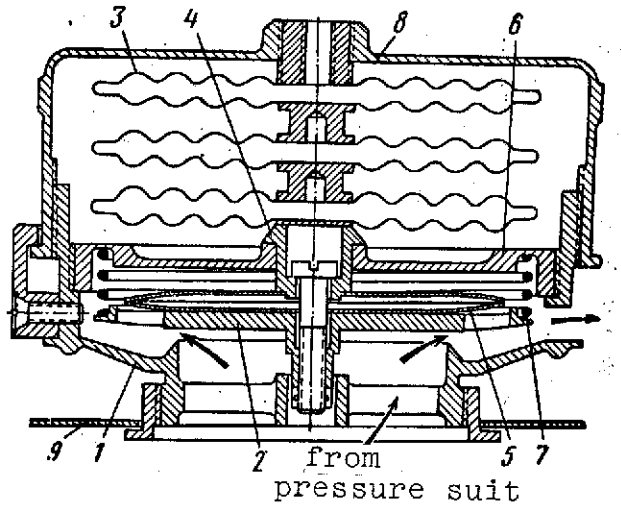


Figure 5.64. Combined pressure regulator [2].

1 — body; 2 — valve; 3 — aneroid stack; 4 — sleeve; 5 — disk type spring; 6 — washer; 7 — spring; 8 — cover; 9 — pressure suit shell.

When the specified differential pressure is established in the pressure suit, the differential pressure unit begins to operate.

If the differential pressure across the valve 2 begins to exceed the force of the spring 5, the valve 2 opens somewhat and the differential pressure in the pressure suit returns to the specified magnitude.

In order to check suit sealing (on the ground), the cover 8 is rotated to block the regulator discharge port and the required differential pressure in the suit is created under the influence of the air supplied to the suit.

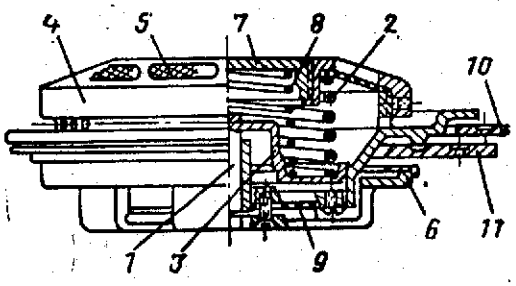


Figure 5.65. Pressure suit safety valve.

1 — body; 2 — spring; 3 — valve disk; 4 — cover; 5 — protective screen; 6 — base; 7 — adjusting washer; 8 — adjusting spring; 9 — screen; 10, 11 — washers for attaching valve to pressure suit.

The spring 7 makes it possible to create in the pressure suit a small differential pressure on the order of 8 — 16 mm Hg to straighten out the pressure suit shell and expand the ventilation gaps.

A safety valve is provided to reduce the differential pressure in the pressure suit if it exceeds the allowable value (Figure 5.65). The valve opens when this pressure exceeds the force of the preloaded springs 2 and 8. /185

In calculations, we should consider that with increase of the safety valve diameter its travel decreases, but at the same time, its sensitivity decreases.

11. Communications Equipment in Pressure Suit

The communications and data transmission equipment used in pressure suits is designed for joint functioning with the communications radio equipment installed in the flight vehicles, and also for transmission to the Earth by means of the telemetry system data on the physiological condition of the crewmembers and operation of the individual pressure suit components.

The pressure suit communications equipment includes: *helmet phones, hermetic communications lead connector,* and *telemetry monitor sensors* (Figure 5.66).

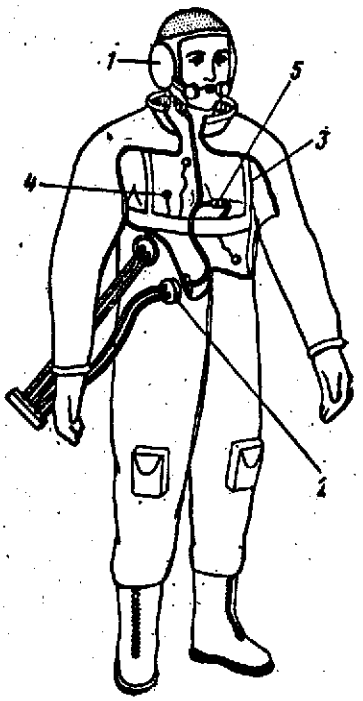


Figure 5.66. Suit communications equipment.

1 — communication helmet phones; 2 — hermetic communications connector; 3 — telemetry belt; 4 — telemetry monitor sensor; 5 — miniature connector.

Helmet phones. The basic elements of the helmet phones are the communication helmet, miniature earphones, one or two microphones with holder or throat microphones, communications leads, and line disconnects.

The communication helmet is made from leather or strong fabric. Its lining is made of serge or other fabric having high hygroscopicity (Figure 5.67).

In addition to the communication helmet which covers the head completely, a lightweight helmet in which the upper part is made from kapron netting is also used (Figure 5.68).

The earphones are mounted in noise insulating cups. The rubber earphone cups provide sound reduction of 10 — 12 dB, and earphone cups with liquid filler reduce the noise by 20 dB.

The earphone cups at the same time protect the ears and skull bones against discomfort caused by earphone pressure during extended wearing of the helmet. The microphones should be located at the corner of the mouth and cannot be more than 10 mm from the mouth. Two microphones are often used to improve radio communication reliability. Communication helmets with throat microphones in place of the conventional microphones can also be used.

Figure 5.67. Leather communication helmet with throat mike.

1 — radio communications connector; 2 — oxygen mask attach buckle; 3 — throat mikes; 4 — sound insulating cups with phones.

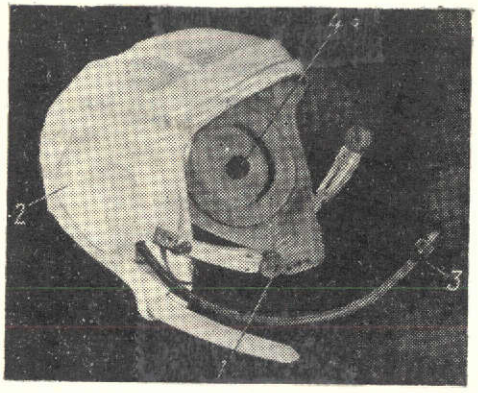


Figure 5.68. Communication helmet with mesh crown for pressure suit.

1 — microphone; 2 — sound insulating cups; 3 — connector; 4 — phones.

Depending on its design, the leather helmet may weigh from 500 to 600 grams, the fabric version will weigh from 400 to 500 grams, and the helmet with netting crown will weigh from 300 to 400 grams. /186

The hermetic communications connector is attached to the pressure suit shell and its outer end terminates in a multipin bayonet plug. Sealing of the connector in the pressure suit shell is accomplished by a clamping washer and rubber gasket. The lines running inside the pressure suit terminate in miniature connectors.

The telemetry equipment in the pressure suit is used for real-time medical monitoring of the wearer's condition and obtaining information on the operation of individual pressure suit components.

TABLE 5.10

PHYSIOLOGICAL MONITORING ABOARD VOSTOK-5 AND VOSTOK-6 SPACECRAFT [13]

Method	Parameter studied	Information obtained	Sensor	Sensor location
Electrocardiography	Heart biopotentials	Biopotentials with amplitude to 2.5 mV and frequency spectrum 0.5 — 40 Hz	Electrodes	Along middle axillary line to left and right at 5th intercostal
Seismocardiography	Heart mechanical work	Chest wall vibrations in frequency range to 18 Hz	Induction seismograph	In sternum region or somewhat to the left
Pneumography	Breathing motions of rib cage	Rib cage perimeter change at 5th intercostal level	Rheostat (carbon)	On rib cage at 5th intercostal level
Electroencephalography	Brain bioelectric activity	Biopotentials with amplitude to 100 μV and frequency spectrum 0 to 18 Hz	Electrodes	Forehead, back and left sides
Electrooculography	Eyeball movements	Biopotentials with amplitude to 500 μV and frequency spectrum from 0 to 18 Hz	Electrodes	Outer corners of eyes
Cutanogalvanic reaction	Skin electrical resistance	Rapid skin resistance variations in 2 to 100 kOhm range	Electrodes	Lower third of skin and sole of foot

The required information is obtained with the aid of sensors installed on the wearer's body or mounted on the pressure suit (Table 5.10).

Figure 5.69. Position of man on water in a space suit with inflatable collar (helmet faceplate down, air required for breathing is drawn in through gaps between faceplate and helmet shell).

12. Survival Equipment

The survival equipment installed on the pressure suit /187
provides assistance in emergency situations:

— during splashdown and when floating on the water;

— after landing under various climatic conditions.

The survival gear, forming part of the pressure suit system and mounted on the suit, includes:

— inflatable collar, jacket, or belt to provide flotation on the water;

— radio set with power supply;

— signal pistol with reserve clip;

— knife, compass, and signal mirror.

The inflatable collar provides flotation for a man in a pressure suit in the water in a comfortable position and the possibility of drifting in the required direction (Figure 5.69).

Additional flotation of no less than 5 — 7 kG is required /188 to maintain the individual's head above the water. Actually, most survival equipment provides additional flotation of 10 to 20 kG.

It is important that the back of the head be above the water. Also important is the position of the floating individual (vertical, inclined, or horizontal). In the vertical position, blood circulation is poor and the body cools off more rapidly.

The existing survival gear maintains the man's body in an inclined attitude at an angle of 20 — 45° to the water surface.

The inflatable collar is packed in a special pocket on the outer garment, which is covered by a flap of the same material as the outer garment.

The inflatable collar is made of rubberized fabric. The volume of carbon dioxide gas required to inflate the collar is 30 — 40 liters. The collar can be infalted by the individual by means of the mouthpiece 1 or is inflated automatically by carbon dioxide gas from the small bottle 4 (Figure 5.70).

The bottle is assembled together with the actuating head (Figure 5.71). In an emergency situation, it is necessary to pull the cord, then the actuating head lever 3 drives the striker piston 4, the needle of which punctures the bottle membrane 5 and initiates gas flow into the collar.

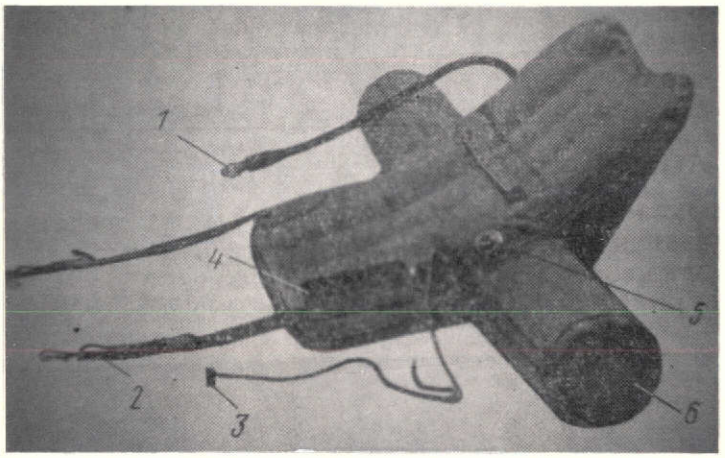


Figure 5.70. Pressure suit inflatable collar.

1 — mouthpiece for inflating collar; 2 — collar attach straps; 3 — manual bottle opening cord; 4 — bottle with carbon dioxide; 5 — safety valve; 6 — lateral sections for increasing lateral stability when afloat.

The flotation collar weighs 700 — 1000 grams, the working pressure in the collar is 0.1 — 0.2 kG/cm^2.

The survival belt of the American G-3C pressure suit is shown in Figure 5.72.

In the stowed position, the belt is packed in a fabric sheath attached to the parachute harness system straps.

The belt is inflated by mouth or is filled automatically from a bottle with gas (usually carbon dioxide) under high pressure. Upon immersion in water, an initiator actuates automatically and initiates gas flow into the belt.

The G-3C pressure suit is also equipped with an inflatable collar which keeps water out from under the pressure suit shell when the astronaut is in the water with his helmet off.

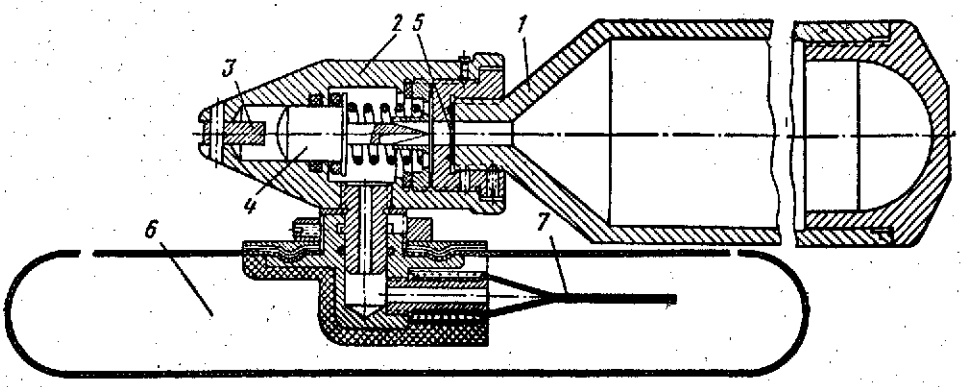


Figure 5.71. Carbon dioxide bottle for filling pressure suit collar.

1 — bottle casing; 2 — actuating head; 3 — lever; 4 — striker piston; 5 — membrane; 6 — collar; 7 — rubber check valve.

The communications radio set consists of a transceiver, power supply, and antenna. /189

In the stowed position, the radio set is stored in a pocket of the outer garment. It weighs about 1 kG.

In addition to the survival gear kept in the pressure suit, *a portable emergency kit* (PEK) is stored in the spacecraft cabin. The composition of the PEK is selected in accordance with the flight vehicle mission and the conditions under which the crew may find themselves in an emergency situation. For example, the PEK for the Vostok spacecraft weighed 40 kG. The PEK for a fighter airplane usually weighs 10 — 12 kG.

13. Weight of Emergency-Survival Pressure Suit

While it is true that all the heavy equipment carried by an individual creates more drawbacks than advantages, weight is particularly important for the pressure suit. First of all, because of the fact that the pressure suit is used aboard modern /190

Figure 5.72. Inflatable collar and life belt of American G-3C pressure suit.

1 — inflatable collar; 2 — life belt; 3 — bottle for filling belt.

flight vehicles which require maximum mobilization of all man's forces.

The eternal question of what should be considered light and what heavy cannot have a unique answer. Obviously, the lighter the pressure suit, the less it tires the wearer.

As pressure suit construction is improved and new materials are created, pressure suit weight will decrease, and it is difficult at the present time to determine the weight of the pressure suit of even the immediate future.

Many elements are not a part of the pressure suit and are used depending on the climatic conditions and the flight mission. These include, first of all, the thermal protection garment, flotation collar, and so on. Therefore, in determining the weight, we should differentiate the weight of the pressure suit proper and the weight of the pressure suit system.

The pressure suit weight is made up of the shell and helmet weight.

The weight of the pressure suit system considers everything that the pilot (cosmonaut) wears as a function of climatic conditions and flight mission.

TABLE 5.11

COMPARATIVE BREAKDOWN OF DIFFERENT FLIGHT GEAR OUTFITS [2]

Winter outfit		Winter outfit with partial pressure suit	
Item	Wt.,kG	Item	Wt.,kG
Fur-lined flight suit	4	Fur-lined flight suit	4
Warm leather boots	2.5	PPS boots	1.5
Protective helmet	2.0	Pressure helmet	3.0
Oxygen mask	0.5		
Gloves	0.25	Gloves	0.25
Warm socks	0.25	Warm socks	0.25
Wool sweater	1.5	Wool sweater	1.0
Pants	0.75	Partial pressure suit	4.0
Underwear	0.5	Underwear	0.5
Total	11.25 kG	Total	14.5 kG

A comparative breakdown of different flight gear outfits is presented in Table 5.11.

14. Tests of Emergency-Survival Pressure Suits

New pressure suit models are subjected to ground and flight tests.

The ground test program includes:

1) static tests to determine the pressure required to cause failure of the pressure suit shell (with restraint system and lacing tight and loose);

2) functional tests to verify operability of all the pressure suit components; /191

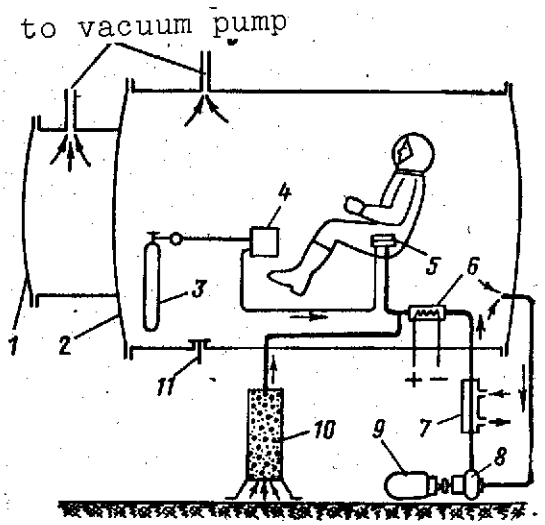


Figure 5.73. Stand for testing ventilated pressure suit in thermobarochamber.

1 — forechamber; 2 — large barochamber; 3 — oxygen bottle; 4 — oxygen regulator; 5 — hose connector; 6 — electric preheater; 7 — cooler; 8 — blower; 9 — electric motor; 10 — moisture remover; 11 — rapid descent valve.

3) dynamic tests to determine the strength and operability of the pressure suit shell and components in case of instantaneous cabin depressurization;

4) verification of effect of velocity head on the pressure suit during ejection;

5) pressure suit testing in thermobarochamber (Figure 5.73) to verify:

— operation of the pressure regulator and determine the differential pressure maintained by the regulator at various altitudes;

— oxygen and carbon dioxide content in the exhaled air and respiration resistance;

— emergency oxygen flow;

— temperature regime, thermal sensation, required oxygen and ventilating air flowrates in the specified temperature range;

— freedom from visor fogging;

6) determination of pressure suit mobility (zones of reachability) should be made under conditions close to reality, in the flight vehicle cabin (or cabin mockup) with the control levers which the pilot will use in flight installed.

In order to obtain a preliminary evaluation, the subject performs several characteristic movements while standing or seated in his chair;

7) tests on the water to determine flotation, stability, ability to drift in the required direction, and thermal protection properties of the pressure suit.

The flight test program includes:

1) verification of the possibility of controlling the flight vehicle in all flight regimes (with and without differential pressure in the pressure suit);

2) check of pressure suit with instantaneous cabin decompression;

3) check of pressure suit in case of emergency egress from the flight vehicle.

15. Typical Pressure Suit Models

Soviet Pressure Suits

The SI-3M mask-type emergency-survival ventilated pressure suit (1953) was designed for flights at altitudes up to 20 km. The working (differential) pressure in the suit is 0.15 to 0.19 kG/cm^2 (Figure 5.74).

The pressure suit is made from rubberized fabric. The helmet with hinged visor is attached to the shell by a bayonet type lock (see Figure 5.33). /192

Figure 5.74. SI-3M pressure suit without outer garment [2].

1 — boot disconnect; 2 — pressure regulator; 3 — communications connector; 4 — fitting for air to g-suit; 5 — oxygen hose to helmet; 6 — ventilation air hose; 7 — balancing hose.

The communication lead connector and the fitting for air supply to the g-suit are located on the left side.

The belt shown in the figure is intended for fitting the pressure suit in length.

The SI-3M suit weighs 9.5 kG (shell 5.0 kG, removable hermetic boots 1.8 kG, gloves 0.4 kG, helmet 2.3 kG).

The SI-3M pressure suit system weighs 14.1 kG (SI-3M pressure suit 9.5 kG, outer garment 1.2 kG, thermal protection garment 1.2 kG, undergarment 0.5 kG, communication helmet 0.4 kG, flotation collar 0.9 kG, other detail parts 0.2 kG).

The aircraft emergency survival pressure suit is equipped with a swiveling helmet and removable gloves (Figure 5.75).

The pressure suit of Yu. A. Gagarin was used for flights aboard the Vostok spacecraft (see Figure 5.41).

The pressure suit shell is multilayer: the restraint layer is fabricated from strong synthetic fabric, the inner hermetic layer is made of thin rubber, the liner (to reduce friction during donning and protect the hermetic shell) is sewn from lightweight fabric (Figure 5.76).

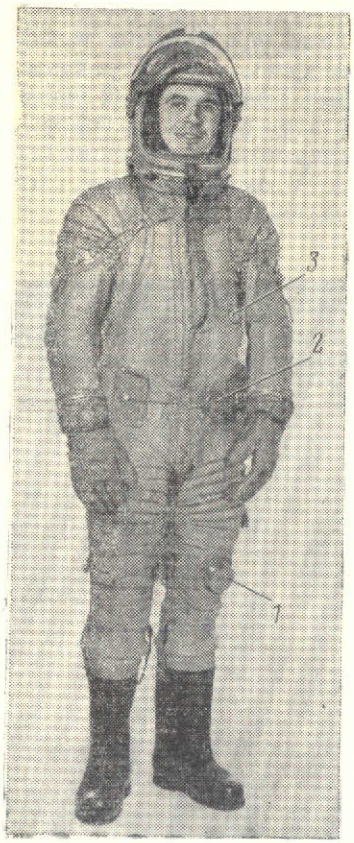


Figure 5.75. Emergency survival pressure suit.

1 — pressure regulator; 2 — restraint system regulator; 3 — safety valve.

Figure 5.76. Pressure suit of cosmonaut Yu. A. Gagarin without outer garment.

1 — pressure regulator (first regime 0.27 kG/cm^2); 2 — restraint system tightener; 3 — oxygen supply hose; 4 — single-point disconnect; 5 — communications plug; 6 — respiration valve.

The opening is located in the front part of the torso.

An electrical connector is provided on the pressure suit shell and inside the pressure suit there is a plug for connecting the leads from the telemetry equipment sensors.

The helmet forms an integrated unit with the shell. In an emergency situation, the helmet visor is lowered into place automatically. The cosmonaut can also raise and lower the visor

manually. The helmet visor glass is double to prevent fogging.

The thermal protection garment is made in coverall form (see Figure 5.51). The hydraulic resistance of the ventilating system does not exceed 150 mm H_2O with air flowrate 150 liters per minute.

The pressure in the suit is regulated by two pressure regulators and a single safety valve, designed for maximum operating pressure 205 mm Hg (differential pressure 0.27 kG/cm^2).

Two miniature earphones are located in the noise isolating cups of the comm helmet. The microphones are mounted on hinged cantilever holders which locate the microphones opposite the corners of the mouth. The radio communication system also provides for the use of throat microphones, which are used in place of the boom microphones during the powered flight segment (with engines running).

Leather boots are worn over the pressure suit.

The emergency-survival equipment of this pressure suit includes: survival (flotation) collar, miniature radio set, signal pistol, and knife. The collar is attached to the outer garment and in the inoperative position is stowed on the back and closed by a flapper valve fabricated from the same material as the outer garment. /193

At the instant of splashdown, the collar is automatically filled with carbon dioxide from the bottle. Manual actuation of the bottle and filling of the collar with air by the astronaut himself is provided.

The suit can be donned with the assistance of a single helper

in 5 — 10 minutes and can be doffed by the astronaut alone.

Space suit weight is 11.5 kG (shell — 7.9 kG; helmet — 3.6 kG).

USA Pressure Suits

The MK-IV pressure suit is an aircraft emergency-survival pressure suit (1955).

The pressure suit is worn over an undergarment and consists of the shell, helmet, removable gloves and boots (Figure 5.77). The pressure suit shell is two-layer. The outer restraint layer is made of nylon fabric, the inner (hermetic) layer is made of nylon fabric impregnated with neoprene rubber.

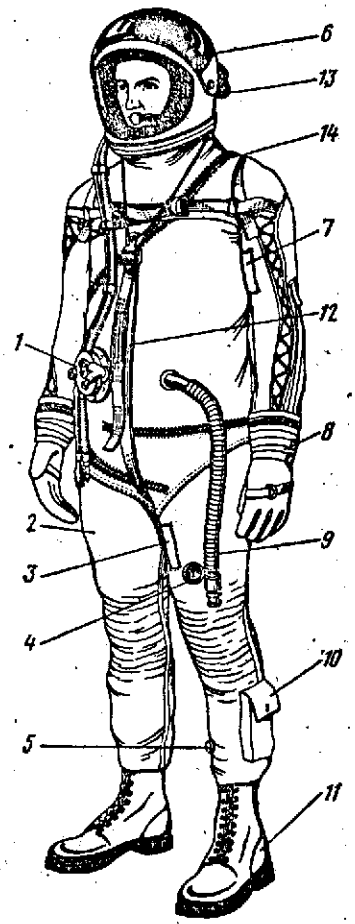


Figure 5.77. American MK-IV aircraft emergency-survival pressure suit.

1 — pressure regulator; 2 — restraint shell; 3 — knife pocket; 4 — pressure indicator; 5 — safety valve; 6 — helmet; 7 — pencil pocket; 8 — gloves; 9 — ventilation air hose; 10 — pocket for heated gloves; 11 — removable boots; 12 — helmet tightener; 13 — oxygen regulator; 14 — hermetic zipper.

A miniature oxygen regulator is mounted on the helmet. The breathing oxygen enters the front part of the helmet. The rear (back-of-the-head) part of the helmet is separated from the front part of the face seal and is ventilated by air. /194

The helmet consists of a plastic shell and tilting visor. A light filter is provided to protect the eyes against blinding. The visor is sealed by a rubber hose which expands and presses against the visor along the entire perimeter.

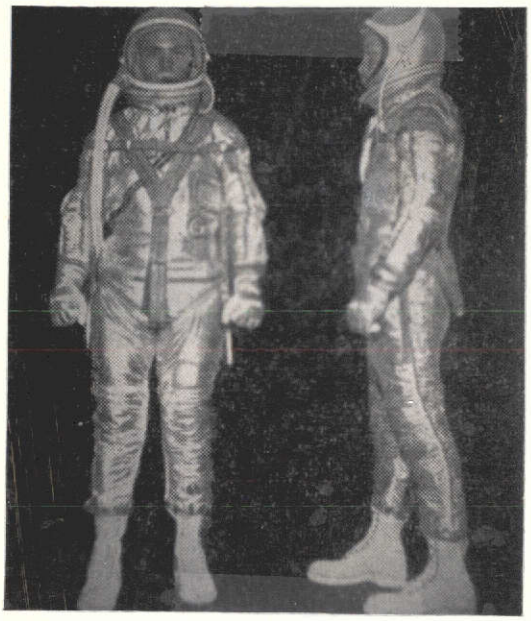


Figure 5.78. American MK-IV pressure suit for flights in the Mercury program.

Earphones and a microphone are mounted inside the helmet. The earphones are built into ear cups which press against the ears and fix the helmet position. As the head is turned, the helmet rotates in an hermetic bearing. The MK-IV pressure suit weighs about 9.0 kG (shell 6.0 kG, helmet 2.4 kG).

A modernized version of the MK-IV pressure suit was used in the space flights in the Mercury program.

The restraint shell of this pressure suit is made from aluminized nylon fabric (Figure 5.78).

Oxygen enters the pressure suit through a fitting located on the left side of the chest. Gases are discharged from the suit through an outlet located on the helmet (Figure 5.79).

A rubber dam is provided to seal the suit when located in the water. Under normal conditions, the dam is rolled up and does not restrict head movement.

The gloves are attached to the hermetic wrist bearings. Lacing is provided on the back side of the gloves for individual fitting. Small electric lamps (5 candlepower) are located on /195 the tips of the first and middle fingers of both gloves to illuminate the instrument panel when in the shadowed portion of the orbit. The inner side of the gloves is covered with soft leather.

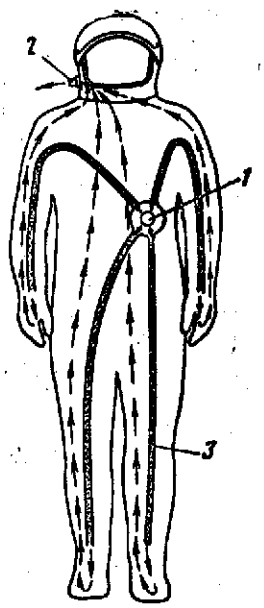


Figure 5.79. Ventilation system of the MK-IV pressure suit.

1 — Oxygen connector; 2 — gas discharge fitting; 3 — ventilation system tubes.

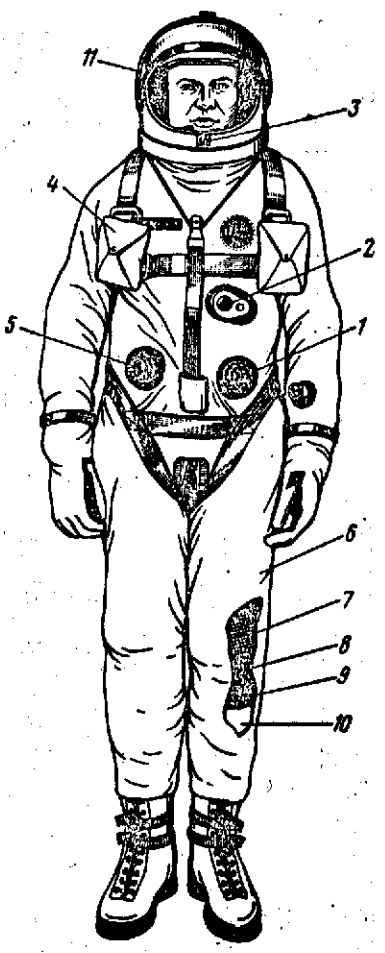


Figure 5.80. American G-3C pressure suit.

1 — oxygen inlet fitting; 2 — communications connector; 3 — feed port; 4 — survival belt; 5 — fitting for gas discharge from suit; 6 — outer garment; 7 — restraint shell; 8 — hermetic shell; 9 — liner; 10 — underwear; 11 — helmet faceplate.

The pressure suit is worn over a cotton undergarment made in coverall form.

The G-3C pressure suit was built for the flights in the Gemini program (Figure 5.80).

The suit is four-layer: an inner layer of nylon fabric acts as a slippery liner, the next layer is the hermetic shell made of rubberized nylon with neoprene coating, the restraint shell is made in the form of dacron netting, and the outer layer (outer garment) is made of nylon (NT-1).

TABLE 5.12

APPROXIMATE WEIGHT BREAKDOWN OF G-3C PRESSURE SUIT

Element	Weight, kG	
	Element	Total
Shell:		8.8
protective shell	1.8	
restraint shell (netting)	2.0	
hermetic shell	2.2	
liner	0.6	
ventilating system	0.6	
instruments and disconnects	1.2	
gloves	0.4	
Helmet		2.8
Other parts		0.1
	Total	11.7 kG

The pressure suit is equipped with a zipper. The glove and helmet disconnects are equipped with hermetic bearings. The boots are made of the same material as the pressure suit shell. The helmet visor is made of 3.1 mm thick polycarbonate. /196

A weight breakdown of the G-3C pressure suit is shown in Table 5.12.

The G-5C pressure suit was used for the Gemini-7 spacecraft flight. It is equipped with a soft helmet joined to the shell by a zipper. The astronaut wears the conventional military pilot helmet directly on his head (Figure 5.82).

The pressure suit is two-layer: the inner pressure-sealing shell is made of rubberized nylon, the outer shell is made of NT-1 nylon. Netting segments which can stretch in one direction only are located at the bend points to improve mobility.

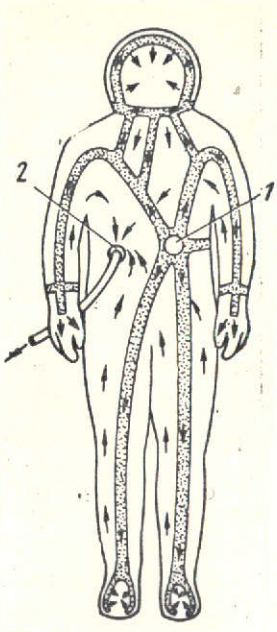


Figure 5.81. Ventilation system of G-3C pressure suit.

1 — oxygen inlet connector; 2 — oxygen outlet connector.

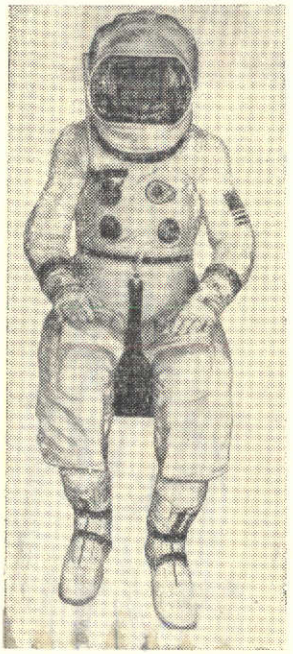


Figure 5.82. American G-5C pressure suit.

The G-5C pressure suit weighs 7.4 kG (shell 3.5 kG, helmet 0.9 kG, gloves 0.3 kG, protective helmet 2.2 kG).

REFERENCES

1. Umanskiy, S. P. Chelovek i kosmose (Man in Space), Voyenizdat, Moscow, 1970.

2. Umanskiy, S. P. Snaryazheniye letchika i kosmonavta (Equipment for the Pilot and Cosmonaut), Voyenizdat, Moscow, 1967.

3. Ivanov, D. I. and A. I. Khromushkin. Sistemy zhizneobespecheniya cheloveka pri vysotnykh i kosmicheskikh poletakh (Life Support Systems for Man in High Altitude and Space Flights), Mashinostroyeniye, Moscow, 1968.

4. Prokof'yev, V. M., et al. "Experimental Studies of the Strength of Sewn Seams of Rubber and Rubberized Fabric Balloon Structures," Kauchuk i rezina, No. 8, 1966.

5. Strekozov, N. P. "Some Questions of the Strength of Conical and Cylindrical Shells Made from Soft Materials," Transactions of 6th All-Union Conference on Shell and Plate Theory (Baku, 1966), Nauka, Moscow, 1966. /197

6. Kosimov, S. A. Ocherki fiziologii truda (Outline of Work Physiology), Meditsina, Moscow, 1965.

7. Woodson, W. E. and D. W. Conover. Human Engineering Guide for Equipment Designers (Russian translation), Mir, Moscow, 1968.

8. Sidorov, O. A. Fiziologicheskiye faktory cheloveka, opredelyayushchiye komponovku posta upravleniya mashinoy (Physiological Factors of Man Which Determine the Arrangement of Machine Control Stations), Mashgiz, Moscow, 1962.

9. Kolesnikov, P. A. Teplozashchitnye svoistva odezhdy (Thermal Protective Properties of Clothing), Legkaya industriya, Moscow, 1965.

10. Ladyzhenskiy, R. M. Konditsionirovaniye vozdukha (Air Conditioning), State Commercial Literature Publishing House, Moscow, 1962.

11. Kutateladze, S. S. and V. M. Borishanskiy. Spravochnik po teploperedache (Heat Transfer Handbook), Energoizdat, Moscow, 1959.

12. Kedrov, L. U. Uteplennaya obuv' (Warm Footwear), Gostekhizdat, Moscow, 1962.

13. Vtoroy gruppovoy kosmicheskiy polet i nekotoryye itogi poletov sovetskikh kosmonavtov na korablyakh "Vostok" (Second Group Spaceflight and Some Results of Flights of Soviet Cosmonauts in the Vostok Spacecraft), edited by N. M. Sisakyan, Nauka, Moscow, 1965.

CHAPTER 6
EXTRAVEHICULAR PRESSURE SUIT

1. Purpose and Requirements

The pressure suit designed for cosmonaut egress from the spacecraft provides the necessary living conditions for the cosmonaut exiting into the surrounding cosmic space for the purpose of: /198

— making scientific observations;

— repairing the spacecraft surface;

— installing or removing various objects;

— assembling orbital stations from individual sections, and so on.

The extravehicular suit (EVS) can be completely autonomous or connected with the spacecraft by a tether, hoses, and umbilicals through which oxygen and electrical power are fed and communication is maintained.

In the autonomous life support system variant, the power sources and means of locomotion are located in a backpack. The cosmonaut can move in any direction relative to the spacecraft.

The construction of the pressure suit shell depends to a comparatively small degree on whether the cosmonaut has an autonomous life support system or everything necessary to support his life activity is supplied to the suit through hoses and umbilicals.

Both general and special requirements are imposed on the extravehicular pressure suit.

General EVS Requirements

1. The EVS must satisfy the general requirements imposed on the emergency-survival pressure suit (see Chapter 5).

2. The suit must be equipped with dosimeters to indicate penetrating radiation magnitude.

3. Provision must be made for transmitting telemetry data to the spacecraft or to the Earth for continuous monitoring of the cosmonaut's condition.

4. For stay in the suit of more than 2 to 3 hours, it is desirable that provision be made for taking liquid food (juices, coffee, water, and so on) and collecting liquid wastes.

Special EVS Requirements

1. The suit must satisfy the special requirements imposed on the space emergency-survival pressure suit.

2. The suit must provide:

— protection of wearer against overheating during stay on the sunny side and against overcooling when located in the shadow;

— protection against damage when encountering meteoric matter with dimensions up to 300 — 400 microns; /199

— protection of the sight organs against the harmful action of solar radiation;

— mobility required to perform the specified operations.

3. The materials used in fabricating the pressure suit must be resistant to extended exposure to the physical factors of cosmic space and not alter their physico-mechanical and optical properties under the influence of vacuum and solar radiation.

4. The suit construction must be reliable and trouble free in operation to the required degree, must have backup systems which are activated automatically in case of an emergency.

Measurements made during the space walk of A. A. Leonov and data obtained during the flights of the American astronauts have shown that working in space involves large energy expenditures.

Thus, during egress into space from the cabin of the Gemini-9 spacecraft, Cernan's pulse rate was 155 while opening the hatch and then increased to 170 (as a function of the effort expended). The highest pulse rate (180) was recorded during closing of the hatch cover. Cernan estimated that the performance of the planned operations in space required four to five times more effort than during training sessions in the barochamber.

During his space walk, the second pilot of the Gemini-11 spacecraft (R. Gordon) expended 70% of his efforts in staying in place while performing operations. His respiration rate reached 40 — 50. His average pulse rate during the space walk was 162, the peak value was 180. Gordon sweated profusely. The experiment lasted 44 minutes (rather than the 107 minutes planned). The peak energy expenditures reached 15 kcal/minute.

Although preliminary, these data indicate that, in selecting the autonomous LSS, it is necessary to start from the condition of supplying breathing oxygen at a rate of 1.5 to 2 liters(s)/minute. The average oxygen flowrate in the course of 3 — 4 hours amounts to 90 — 120 liters(s)/hour and will compensate for energy expenditures ranging from 450 to 600 kcal/hr.

Since heat release of 15 — 20 kcal/min is possible only for a short time period and the cooling techniques presently known cannot remove heat in this quantity, an average heat removal rate of 450 — 600 kcal/hr is usually used as a design basis.

2. Extravehicular Pressure Suit Configuration

The requirements imposed on the extravehicular pressure suit make it necessary to introduce new elements in the suit construction:

— outer garment having the required characteristics in regard to solar radiation reflection and absorption;

— vacuum-barrier thermal insulation (VBTI);

— anti-meteoroid garment;

— backup hermetic shell;

— helmet visor capable of protecting the cosmonaut's eyes against the harmful effects of cosmic space.

Outer Garment

The outer garment is the external protective layer which protects the pressure suit against possible mechanical damage when leaving the spacecraft.

The external surface of the garment must have the required optical properties and reflect the Sun's radiant energy to the greatest possible degree.

The materials from which the garment is made must be temperature resistant and must not alter their physico-mechanical properties upon contact with the spacecraft surface (about ±150° C). /200

Since the amount of heat penetrating into the suit will be small in comparison with the amount of heat reflected and absorbed by the external surface of the outer garment (as a consequence of the high thermal resistance of the pressure suit), the temperature of this surface will approach the equilibrium adiabatic wall temperature, i.e.,

$$T_{og}=\sqrt[4]{\frac{A_s q_s S_{sn}}{\varepsilon\sigma_0 S_r}},$$

where A_s is the coefficient of solar radiation absorption; q_s — the solar constant (1200 kcal/m^2/hr), ε — the emissivity; σ_0 — the Stefan-Boltzmann constant ($\sigma_0 = 4.9\cdot10^{-8}$ kcal/m^2/hr/°C^4).

The quantity A_s/ε will have a minimum value for garments best satisfying the stated requirements.

For white fabric $A_s = 0.27$, $\varepsilon = 0.9$, and $A_s/\varepsilon = 0.3$. The optical characteristics of some fabrics are presented in Chapter 8.

In selecting the material for the outer garment, preference should be given to materials having the highest self-ignition temperature, minimum burning rate under the given conditions, and which are self-extinguishing (brief information on the fire

Figure 6.1. Pressure suit of cosmonaut A. A. Leonov. 1 — oxygen supply hose (when in ship); 2 — LSS backpack.

resistance properties of various materials is presented in Chapter 8). A garment made of glass fiber will best meet the stated requirements.

The outer garment is made in coverall form (Figure 6.1) from a strong fabric (lavsan,phenylon, dacron) which has good tear strength (no less than 10 — 15 kG).

The coverall is attached to the pressure suit by lacing or velcro-type fasteners.

Gathers are provided or "orange peels" (gores) are installed at the joints so that the garment will not limit mobility. The garment is provided with pockets (Figure 6.2) for storing personal articles, documents, and other items.

Vacuum Barrier Thermal Insulation

Vacuum barrier thermal insulation (VBTI) is used to protect the cosmonaut against overheating or chilling when egressing from the spacecraft into cosmic space.

The following requirements are imposed on the VBTI:

— protection against heat penetration into the pressure suit when in the sunlight and heat loss when in the shade (the term multilayer insulation has also been used in the literature to describe VBTI);

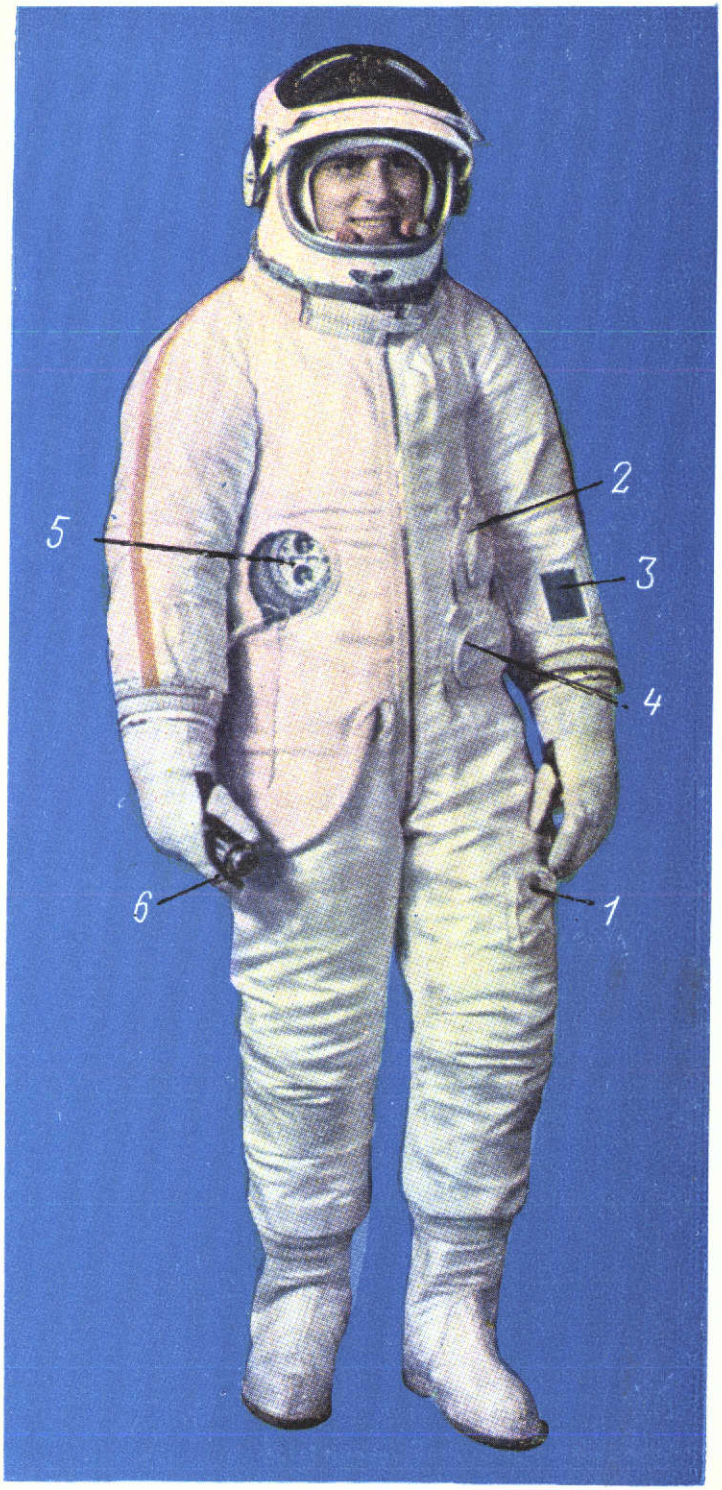


Figure 6.2. Pressure suit for Soyuz spacecraft (without autonomous LSS).

1 — pocket; 2, 4 — pressure regulator protective flaps; 3 — mirror; 5 — single point disconnect; 6 — communications connector.

— good compatibility with the pressure suit (the VBTI must not limit man's mobility in the pressure suit); /201

— minimum weight and size along with maximum thermal resistance;

— adequate mechanical strength;

— inflammability;

— high chemical resistance to the physical factors of cosmic space.

The VBTI consists of a series of barriers located in an evacuated space. In this case, heat is transmitted in three ways: by radiation, residual gas thermal conduction, and solid body thermal conduction.

The screening action of the multilayer construction is shown in Figure 6.3. Let us assume that, between the two parallel surfaces 1 and 2, there is a thin heat-conducting material barrier such that the difference of the temperatures on its two sides (surfaces) can be neglected. If we assume that the intermediate medium is a vacuum and the emissivities of the surfaces 1 and 2 are the same and equal to ε, then the effective emissivity is determined from the formula [1]

$$\varepsilon_{ef} = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} = \frac{\varepsilon}{2-\varepsilon}; \qquad (6.1)$$

If there is no barrier, the resultant thermal flux radiated by body 1 to body 2 is calculated using the formula

$$q_0 = \varepsilon_{ef}\sigma_0(T_1^4 - T_2^4), \qquad (6.2)$$

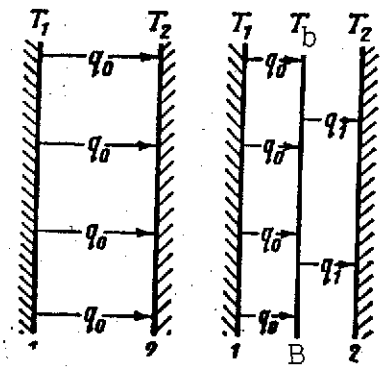


Figure 6.3. Radiant heat exchange scheme in presence of barrier [9].

where σ_0 is the blackbody radiation constant.

When a barrier is installed between surfaces 1 and 2, its temperature takes some value T_b and the amount of heat received by the barrier from surface 1 will equal the amount of heat transmitted to surface 2

$$q_1=\varepsilon_{np}\sigma_0(T_1^4-T_3^4)=\varepsilon_{np}\sigma_0(T_3^4-T_2^4). \tag{6.3}$$

Hence, $T_3^4=\frac{1}{2}(T_1^4+T_2^4)$.

Substituting this value into (6.3), we find the amount of heat transmitted by surface 1 to surface 2 in the presence of a single barrier between them

$$q_1=\varepsilon_{np}\sigma_0\left(T_1^4-\frac{1}{2}T_1^4-\frac{1}{2}T_2^4\right)=\frac{1}{2}\varepsilon_{np}\sigma_0(T_1^4-T_2^4)=\frac{1}{2}q_0. \tag{6.4}$$

Thus, a single barrier reduces the radiant heat exchange intensity by a factor of two. In the presence of n barriers $q_n=q_0/n+1$.

The kinetic theory of gases usually considers two extreme cases of heat transport by gases, namely $L \ll \delta$ and $L \gg \delta$ (L is the molecular mean free path in the gas, δ — the distance between the heat exchanging surfaces). The ratio L/δ is called the Knudsen number Kn.

The mean free path L is connected with the gas pressure p and temperature T by the relation /202

$$L=\frac{K}{p}\frac{1}{1+\frac{T_y}{T}}, \qquad (6.5)$$

where K and T_y are constants which depend on the kind of gas. For air $K = 8.42\cdot10^{-4}$ kG/m, $T_y = 113$ K.

Under the condition $Kn \ll 1$, the thermal conductivity of the gas is independent of its pressure and is connected with the dynamic viscosity μ and specific heat c_v of the gas by the relation [2]

$$\lambda=\varepsilon\mu c_v, \qquad (6.6)$$

where

$$\varepsilon=\frac{9k-5}{4}, \qquad (6.7)$$

$k = c_p/c_v$ is the ratio of the isobaric and isochoric specific heats.

At sufficiently low pressures, when the condition $Kn \gg 1$ is met, the gas molecules travel from wall to wall without encountering one another. Under these conditions, the amount of heat transferred is proportional to the number of molecules taking part in the heat exchange and therefore to the pressure of the gas.

With increase of the distance between the walls, the molecular path increases and the number of molecules per unit surface area also increases. As a result, the heat transfer rate is

independent of the distance between the walls. Therefore, here the concept of the thermal conductivity, expressing the conductivity of matter referred to unit thickness of its layer, is not applicable. The kinetic theory of gases leads in the case Kn $\gg$ 1 to the following solution for heat transfer between two surfaces which are parallel or located one inside the other

$$Q=\alpha\frac{k+1}{k-1}\sqrt{\frac{\bar{R}}{8\pi}}\frac{p}{\sqrt{MT}}S_1(T_2-T_1); \tag{6.8}$$

$$\alpha=\frac{1}{\frac{1}{\alpha_1}+\frac{S_1}{S_2}\left(\frac{1}{\alpha_2}-1\right)}, \tag{6.9}$$

where Q is the amount of heat transferred, α — the accommodation coefficient, $\bar{R}$ — the universal gas constant, M — the molecular mass, S_1 and S_2 — the surface areas.

The subscripts "1" and "2" relate, respectively, to the inner and outer surfaces.

The accommodation coefficient accounts for the degree of completeness of the heat exchange between the gas molecules and the surface.

The accommodation coefficient is always less than one.

In Dewar vessels (for liquid oxygen), the distance between walls is in the range of 10 — 20 mm. In this case, the heat transfer by the gas begins to decrease for pressures below $5.02\cdot10^{-5}$ kG/cm^2 and for pressures below $1.02\cdot10^{-6}$ kG/cm^2 is proportional to the pressure. To reduce the heat transfer by residual gas thermal conduction to a very small magnitude (no more than 5% of the heat transfer by radiation), it is necessary

to maintain a pressure of no more than $1.02 \cdot 10^{-8}$ kG/cm^2 (0.001 N/m^2) or $7.5 \cdot 10^{-6}$mm Hg in the space between the Dewar walls [2].

Heat transfer by thermal conduction through a solid body is described by the Fourier law and depends primarily on the value of the thermal conductivity λ.

In VBTI, all three heat transfer means are mutually interrelated and inseparable. At the same time, in the general case, a quite acceptable approximation is obtained by considering the heat flux through VBTI as the sum of three individual independent components /203

$$q_0 = q_g + q_s + q_r, \qquad (6.10)$$

where q_0 is the overall heat flux through the VBTI, q_g — the heat flux transmitted through the gas, q_s — the heat flux transmitted through the solid body, q_r — the heat flux transmitted by radiation.

Analysis of (6.10) makes it possible to formulate the basic requirements which VBTI must meet.

1. The residual gas pressure in the insulation layers must not exceed $1 \cdot 10^{-4}$ mm Hg (Figure 6.4).

2. The barrier emissivity must have the lowest possible value (less than 0.03 — 0.05).

3. The interlayer material must have the lowest possible thermal conductivity and must provide the minimum number of contacts with the barriers and the smallest possible contact area.

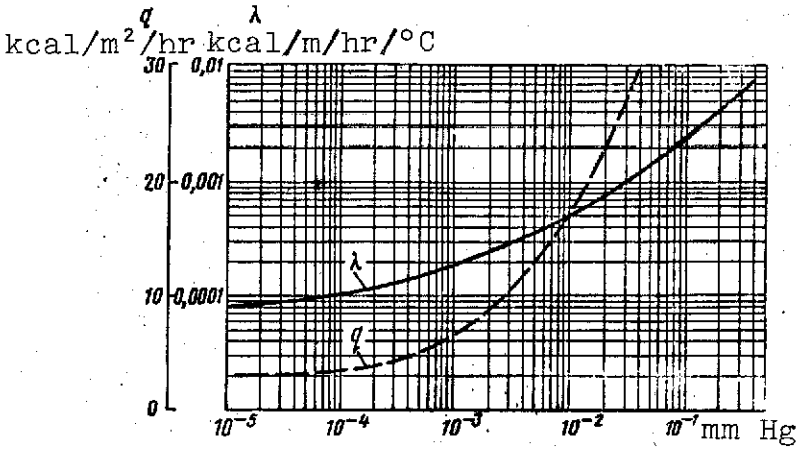


Figure 6.4. Dependence of VBTI thermal conductivity (λ) and specific thermal flux (q) on vacuum level.

4. The barrier and interlayer materials must have the lowest possible gas evolution.

In practice, aluminum foil 10 microns thick (GOST 618-62) is used in VBTI operating at temperatures below 550° C. Aluminum foil has comparatively low weight, low cost, and the required emissivity. At working temperatures from 550 to 1200° C, barriers are made from foil of the nickel alloy NIVO-3TUTsMO-03 No. 88-67 with thickness 5 — 6 microns (weight 54 g/m²). Barriers of polyethylene terephthalate (PETP) film meeting MRTU 6-05-1108-68, coated with aluminum on one side (PETP-OA) or on both sides (PETP-DA), are used widely at temperatures of ±150° C. They have low gas evolution in vacuum at temperatures below 150° C. The aluminum is deposited on the film in vacuum in accordance with 65TU68 and the thickness of the deposited aluminum layer is on the order of 0.03 — 0.05 microns. Film 5 — 12 microns thick is used for VBTI. The advantages of film in comparison with metallic barriers include high strength, low weight (one square meter of five-micron-thick film weighs seven grams), and also the low thermal conductivity of the material itself, which permits its use without interlayer material between

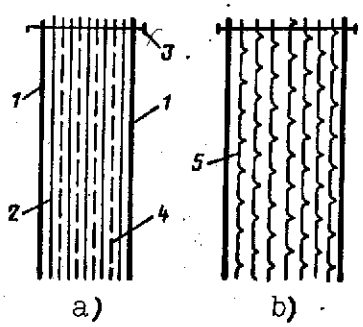


Figure 6.5. VBTI packet.
a — with netting (voile) interlayer; b — corrugated film without interlayer; 1 — protective fabric; 2 — smooth film; 3 — stitching threads; 4 — netting; 5 — corrugated film.

the barriers. The barriers are given a corrugated surface (Figure 6.5) to reduce the area of contact between neighboring layers.

Fibrous materials of the glass-voile type meeting MRTU 6M-885-62 are used at the present time as interlayers in VBTI. The glass-voile is made from glass fibers of diameter up to 10 microns (weight no more than 7 g/m^2). Glass-voile made from quartz fiber is strong, does not burn, and does not evolve a large quantity of gas in a vacuum. /204

Insulation made from PETP film and aluminum foil backed with glass voile is widely used. Backing of the film with the glass voile takes place in vacuum forming machines at temperatures on the order of 150° C using metallic netting as the substrate. Here, bonding of the barrier interlayer is provided by an adhesive material located in the interlayer. At the same time, the barrier and interlayer take on a corrugated surface. The possibility of weld-bonding the combined material simplifies the technological process of thermal insulation fabrication. Such material can be used to fabricate cylindrical, spherical, and conical shells corresponding to the shape of the part being insulated. This makes it possible to maintain isothermicity of the individual layers over the entire surface of the insulation. Layer by layer application of insulation in the form of individual shells, cut to pattern, guarantees maintenance of the packing density corresponding to the uncompacted state.

The following characteristics, shown in Table 6.1, were obtained as a result of studies of the physical and mechanical properties of VBTI.

TABLE 6.1

BASIC VBTI CHARACTERISTICS

Material		Optimum packing density cm^{-1}	Effective thermal conductivity $\lambda = 10^5$ kcal (m/hr/°C)
Barrier	Interlayers		
Film PETP-OA	glass voile	25 — 35	5.5
Film PETP-DA	glass voile	25 — 35	4
Film PETP-OA, corrugation 4×1		10 — 15	10
Film PETP-DA, corrugation on 4×1 grid		10 — 15	6
Aluminum foil	glass voile	30 — 40	5 — 7
Aluminum foil 4×1	glass voile	10 — 15	7
Nickel foil	staple quartz fiber cloth	10	6

NOTE: Effective thermal conductivity values are for temperatures $T_1 = 20$ and $T_2 = -196°$ C, in vacuum less than $1 \cdot 10^5$ mm Hg.

The use of VBTI in pressure suits imposes several limitations on the use of interlayer materials. For example, the use of barriers made of aluminum foil and interlayers made of glass fiber materials is precluded.

VBTI consisting of metallized polymer film and interlayers in the form of netting (voile) also made from polymer materials (kapron) is used in pressure suits.

Both VBTI fabrication technique and its attachment technology have a significant influence on VBTI effectiveness. The barrier packing density (degree of compaction) is very important.

With increase of the packing density, the solid body conduction increases while the conduction owing to radiation decreases. For each VBTI type there is an optimum packing density for which the effective thermal conductivity has the minimum value. Experience shows that, as a rule, the optimum packing density corresponds to the packing density of the free-lying (unloaded) VBTI packet.

External mechanical loading caused by the action of atmospheric pressure, cosmonaut weight, sewing, and so on, increases the insulation packing density considerably (Table 6.2), which leads to increase of the effective thermal conductivity by several orders of magnitude. The use in VBTI of corrugated metallized films and interlayers in netting form provides nearly 100% recovery of the packet properties when the mechanical load is removed.

VBTI effectiveness depends, to a considerable degree, on the temperature. Experimental and theoretical data show that the thermal flux passing through VBTI is, to a considerable degree, a function of the wall temperature to the fourth power. /205 This indicates that, with temperature increase, the heat transfer through VBTI is accomplished primarily by radiation.

The disadvantages of multilayer thermal insulation made from polymer film include combustibility and poor abrasion resistance. All these factors lead to rapid deterioration of VBTI thermal protective properties during use [11].

As a result of tests conducted in the USA, the following have been recommended [11]:

a. reflective barriers of 0.5 mm thick polyamide film with 500 — 800 Å thick aluminum coating or 500 Å thick germanium

TABLE 6.2
VBTI PACKING DENSITY AS FUNCTION
OF APPLIED EXTERNAL LOAD

VBTI type	Load, kG/cm^2			
	0.01	0,1	0.2	0.4
PETP-OA (DA) film 12μ thick, 4×1 corrugation, and kapron tricotage netting	20	50 — 55	65	70
PETP-OA (DA) film 5 μ thick and kapron tricotage netting	50	85	90	90

coating. Barriers made of polyamide film with 1000 Å thick gold coating applied to both sides have good thermal protection properties;

b. glass-voile interlayers, which provide the required strength and inflammability;

c. VBTI consisting of 7 — 8 barriers and interlayers; /206
such a combination provides the required thermal protection during cosmonaut egress from the spacecraft cabin into open space;

d. all newly developed designs should be tested in cyclic bending under conditions simulating actual conditions.

VBTI, together with the pressure suit shells, provides the required protection against damage by meteoric matter.

Another critical parameter defining the effectiveness of VBTI operation is the residual gas pressure between layers. The effective thermal conductivity of VBTI increases relatively rapidly with pressure increase in the system above $1 \cdot 10^{-3}$ — $1 \cdot 10^{-4}$ mm Hg. The gas pressure between VBTI layers may remain

at a relatively high level because of high gas evolution of the VBTI components, restricted gas escape from the space between the layers, and gas leakage from the pressure suit.

The use of barrier perforation reduces significantly the gas pressure between layers in VBTI packets.

The optical properties of the pressure suit have a large influence on the thermal fluxes to and from the pressure suit surface. The use of various spectrally selective coatings reduces solar energy absorption while retaining the radiating capability in the IR region at a high level.

Study of heat input when the cosmonaut is near the spacecraft shows that the thermal loading increases by 20% while on the sunny side and decreases by 30% in the shadow. Increase of the thermal loading takes place basically because of solar energy reflected from the spacecraft surface, and also because of indirect radiation emanating from the spacecraft itself. The radiant heat exchange with the spacecraft may be taken to be zero when the cosmonaut is more than 1.5 meters from the ship.

In order to carry out the thermal calculations associated with VBTI use in engineering constructions, including cosmonaut pressure suits, it is necessary to have the following data for the selected VBTI type:

1. Dependence of VBTI packet thickness h on the number n of layers, $h = f(n)$.

2. Dependence of packing density on the applied external load P_{ex}, $n = f(p_{ex})$ (see Table 6.2).

3. Dependence of effective thermal conductivity on packing density and boundary temperatures $\lambda = f(n_1 T_1 T_2)$.

4. Dependence of effective thermal conductivity on vacuum level $\lambda = f(p_{vac})$ (see Figure 6.4).

Knowledge of all these properties of the insulation permits selecting the most effective VBTI type and number of layers required to ensure the pressure suit thermal regime.

In pressure suits, VBTI is used:

— in the form of a coverall worn over the shell;

— as interlayers built into the structure of footwear or gloves;

— as mittens worn over gloves;

— for protection of the LSS components (pack, tubing, communications lines, etc.).

In fabricating the coverall, it is necessary to provide insulation attachment and, at the same time, maintain high insulation effectiveness. It is difficult to satisfy these requirements, since improvement of the insulation attachment leads to its compaction and, consequently, to increase of the thermal conductivity.

Attachment of the individual VBTI elements is accomplished /207 along the perimeter by stitching or bonding. The enclosure is attached with the aid of a kapron fitting which is inserted through looped tape.

The coverall weight depends on the materials used and number of barriers. If we assume that the film thickness is 10 microns, weight 12 g/m^2, then for 10 layers (surface area 2.3 m^2) the weight is:

— film (10 layers) — 300 g

— protective fabric (50 g/m^2) — 250 g;

— attachment details — 200 g;

Total — 750 g.

Meteoroid Garment

The meteoroid (anti-meteoroid) garment is designed to protect the cosmonaut against the impact of meteoric matter, which is possible when the cosmonaut egresses into open space.

Meteoric matter (body) impact may lead to depressurization of the pressure suit, mechanical damage to the structure, fire, blinding flash, and thermal (skin) burns. All these phenomena are being studied at the present time. According to data published in the literature, we can speak with sufficient degree of precision only of the penetrating effect of a meteoric body, as a result of which suit depressurization takes place.

Investigation of the effect of high velocity particles on materials is carried out both by developing the theory of their impact and by conducting experiments in special facilities.

An important parameter in evaluating meteor hazard is the probability of retaining pressure suit shell hermeticity

$$P_0 = \exp(-NS\tau\eta K), \qquad (6.11)$$

where P_0 is the probability of retaining shell hermeticity upon collision with a meteorite, S — the pressure suit surface area in m^2, τ — the exposure time in seconds, η — the shielding action of the Earth relative to the pressure suit, K — the reliability coefficient.

The theoretical mass of the meteoritic matter can be obtained by combining (1.3) and (6.11)

$$m=(\ln P_0/aS\tau\eta K)^{1/\beta}. \tag{6.12}$$

Example. To ensure safe egress from the spacecraft for a period of two hours, we can take the following values of the quantities appearing in (6.11)

$$P_0=0{,}999;\quad \eta=0{,}5;\qquad S=2\ м^2;\quad K=1{,}0;\qquad \tau=7200\ \text{sec}$$

From the value found for the mass m of the meteorite and the assumed values of its average velocity and average density, we find the meteorite energy which must be absorbed by the pressure suit shell or protective layer.

Many investigators have derived formulas for determining crater depth during impact. In the formula proposed by Biork, the penetration depth of an aluminum particle in an aluminum target upon impact with the velocity v is [12]

$$h=1{,}09\,(mv)^{1/3}, \tag{6.13}$$

and for an iron particle in an iron target

$$h=0{,}606\,(mv)^{1/3}, \tag{6.14}$$

where h is the depth and radius of the hemispherical crater formed in cm, m — the mass of the spherical particle simulating

the meteorite in g/s^2m^{-1}, ν — the particle impact velocity in km/sec^{-1}.

In later studies, Biork gives a formula for determining penetration depth for an iron target with account for both particle and target density

$$h = 0{,}0404 \left(\frac{\gamma_{met}}{\gamma_{tar}}\right)^{1/3} (mv)^{1/3}, \qquad (6.15)$$

where γ_{met} is the specific weight of the meteorite in g/cm^3, γ_{tar} — the specific weight of the target material in g/cm^3.

Eichelberger and Gehring propose to take into account target strength, specifically its Brinell hardness. Their formula has the form

$$h = 0{,}961 \cdot 10^{-3} \left(\frac{mv^2}{HB}\right)^{1/3}, \qquad (6.16)$$

where h is the penetration depth in cm, m — the meteorite mass in g/s^2m^{-1}, HB — the Brinell hardness, v — the meteorite velocity.

The Soviet scientists Stanyukovich, Andriankin, Titov, and others, have made studies of meteorite interaction with a target [3, 4].

The data of theoretical calculations do not always agree with the results obtained in tests on real specimens.

This is obviously explained, first of all, by the fact that the crater depth depends on many factors whose influence is difficult to take into account by mathematical analysis. Therefore, in determining the protective properties of any

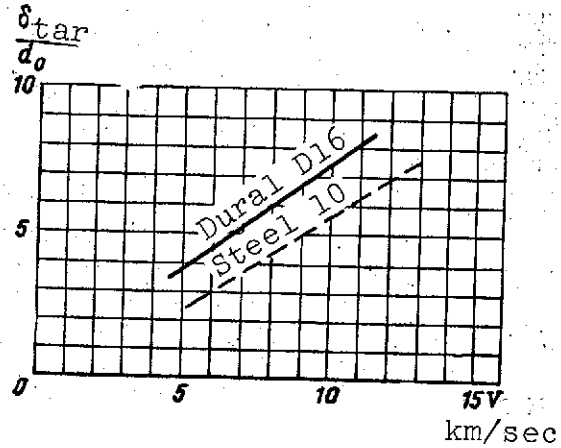


Figure 6.6. Effect of steel spherule impact (see Chapter 5 of [1]).

δ_{tar} is the material (target) thickness; d_0 — the steel spherule diameter.

particular construction preference is given in large degree to test results.

Facilites available at the present time permit particle acceleration to speeds of 20 to 30 km/second.

Figure 6.6 shows the results of steel spherule impact on steel-10 and D16 aluminum alloy targets. For a speed of 10 km/sec, the steel spherule is capable of penetrating a steel target whose thickness is 5.5 spherule diameters and a D16 aluminum target whose thickness is 7.5 diameters. In determining the penetrating effect of a glass spherule of diameter d (simulating impact of a stony meteorite), it was found that, for a speed of 5.8 km/sec, it penetrates a D16 alloy target 2.9 d thick, a steel-10 target 1.28 d thick, and a U12A steel target 1.45 d thick. /209

When penetrating an organic glass target, the thickness of the penetrated material amounts to 12 penetrating particle diameters for particle velocity 11 km/sec.

When impacting an aluminum alloy target, the crater has the form of a cylinder surrounded by a network of microcracks, and the cylinder diameter is two to three times greater than the diameter of the impacting particle.

The physics of the phenomena which arise during particle impact on a porous material are different than in the case of impacts on a solid body [3]. In the porous material, the

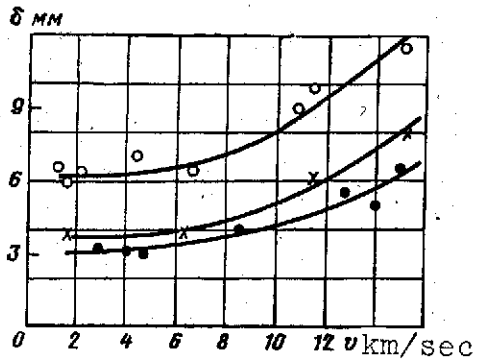


Figure 6.7. Penetration of aviation felt by high velocity particles [10].

particle (glass spherule) diameter: O — 500 μ; × — 420 μ; ● — 250 μ.

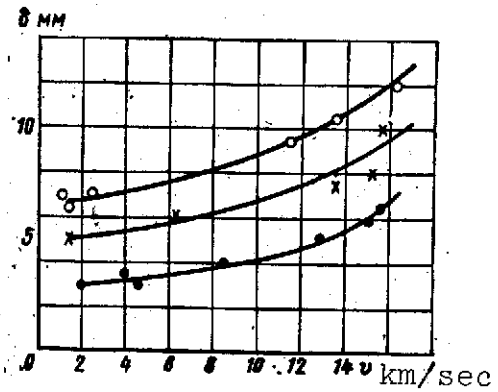


Figure 6.8. Penetration of rubber by high velocity particles [10].

particle (glass spherule) diameter: O — 500 μ; × — 420 μ; ● — 250 μ.

particle, acting like a piston, compresses the material ahead of itself and initially closes the pores, and then travels as if it were in a solid material. The temperature rises (to 10^7 °K) during pore closing. The thermal pressure, similar to the pressure of a highly heated gas, retards particle penetration. In the speed range up to 15 km/sec, particle penetration into a porous medium is analogous to the process of penetration into a gas (so-called gasdynamic flow), in this case resistance proportional to v^2 acts on the particle [4].

We see from the curves shown in Figures 6.7 and 6.8 how the penetrated thickness of aviation felt and foam rubber varies as a function of particle (glass spherule) flight speed.

The pressure suit is a multilayer structure consisting of various materials. Upon impact with the first wall, the particle shatters and its kinetic energy is distributed among several particles, as a result of which the probability of damage to the second layer diminishes.

Experimental studies show that an aluminum spherule breaks /210
up when striking an aluminum plate having thickness one tenth the spherule diameter for velocities from 6 to 20 km/sec. The glass spherule breaks up when striking ethylene terphthalate film having thickness 0.4% of the spherule diameter at a velocity of only 2 km/sec.

The degree of fabric damage depends on fiber thickness and their weave density. If the particle diameter is less than or equal to the thread thickness, the degree of damage is greater.*

Meteorite protection of an American pressure suit is provided by a packet consisting of:*

— protective garment — 180 g/m^2;

— 3 mm thick nylon felt — 270 g/m^2;

— VBTI (seven layers of aluminized mylar of thickness about 6 μ — 190 g/m^2;

— restraint shell (netting) — 100 g/m^2;

— rubberized nylon fabric — 280 g/m^2;

Total — 970 g/m^2

Pressure Suit Shell

More stringent requirements are imposed on the shell of the pressure suit for egress into space than on the shell of the emergency-survival pressure suit in regard to hermeticity and resistance to the factors of cosmic space.

Two hermetic shells are used in some pressure suits to increase reliability. The second shell is a reserve and comes into operation after damage of the primary (outer) shell. This

*AIAA Paper, No. 366, 1969.

is achieved by installing on the reserve shell a pressure regulator which begins to operate only after the pressure in the pressure suit drops below a set level. The pressure regulator maintains a given 0.27 kG/cm^2 differential pressure in the suit. The pressure regulator installed on the reserve shell is open and does not prevent free discharge of the air.

In case of primary shell pressure loss, the pressure regulator (valve) is activated and a pressure of no less than 0.25 kG/cm^2 is maintained in the pressure suit.

A pressure of 0.4 kG/cm^2 can be created in the pressure suit with the aid of the regulator. To do this, it is necessary to first close the regulator by rotating the cover.

The American designers proceeded similarly. In the Gemini-4 flight, the G-4C pressure suit for egress into space differed from the G-3C suit in the presence of VBTI, meteorite garment, and an additional light filter.

3. Individual Means for Maneuvering in Space

General Information

In the near future, the cosmonauts aboard satellite spacecraft will need to perform the following operations:

— erection and assembly of spacecraft sections delivered from the Earth;

— repair, installation, and replacement of units on the outer surface of the craft; /211

— transfer from one spacecraft to another in order to assist or replace the crew.

The results of studies made by Leonov, White, and other cosmonauts have not answered the question of the extent to which man exposed to weightless conditions without being connected with the spacecraft traveling in space can move in the required direction and retain a selected position. The cosmonaut traveling alongside the spacecraft need only carelessly push away from the latter and he will begin to rotate uncontrollably. The rotation will not stop until some force stops it.

If the cosmonaut decides to move a considerable distance from the spacecraft, it would appear that his fellow cosmonaut aboard the vehicle could pull him into the cabin using a tether. But studies have shown that the cosmonaut who is pulled into the ship with the use of a tether may be injured severely if suitable safety measures are not taken. As he travels together with the spacecraft around the Earth, the cosmonaut actually also revolves around the spacecraft. Therefore, if he is pulled toward the vehicle on the end of a tether, he begins to rotate faster and faster around the spacecraft as the tether is shortened. The same forces come into play which force, for example, a spinning figure skater to accelerate his rotation when his arms are brought closer to his body.

At the present time, special propulsive units equipped with a stabilization system are being developed to stabilize the cosmonaut position when outside the vehicle and also to enable him to maneuver. The stabilizing device aids in maintaining normal cosmonaut position (head up) and eliminates any rotation.

The systems for cosmonaut maneuvering in space and for stabilizing his position may be made in the form of:

— a reactive thruster (pistol) which the cosmonaut holds in his hand. The required impulse is created by the reactive thrust which arises during thruster operation;

— a powerplant equipped with a large number of reactive thrusters (nozzles). Such devices can maintain automatically a specified direction and permit conversion to manual control if necessary.

Automatic stabilization in all planes can be provided by three gyros. The signal taken from the gyro is fed through an amplifier to the control channels of the corresponding nozzles. The nozzle is activated if the signal exceeds a set level and compensates for disturbance in the limits of ±5°.

Compressed gas or hydrogen peroxide (H_2O_2) can be used as the fuel (working fluid). A kilogram of hydrogen peroxide is capable of creating an impulse of 100 kG/sec. The total powerplant impulse (with 13 — 16 kG of fuel available) is equal to 1300 — 1600 kG/sec.

According to USA specialists, cosmonauts equipped with such thrusters can move cargoes about in orbit and place them in the position required for assembly.

Since the unit operates continuously, the cosmonaut's hands are freed. He enters into the control process when translational displacement or change of orientation are required.

Description of the systems for maneuvering in space goes beyond the scope of our subject matter; therefore, in the following, we present only some brief information on this configuration which may be useful to the pressure suit designer. /212

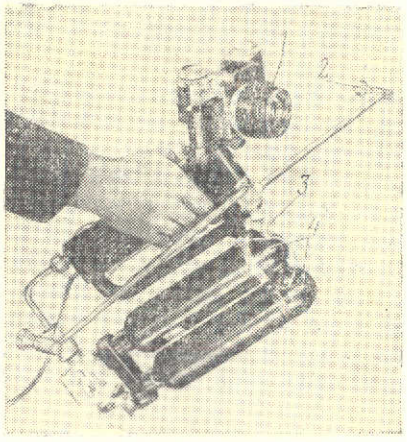


Figure 6.9. "Zip" reactive pistol for maneuvering in space (USA).

1 — camera; 2 — forward nozzle; 3 — reverse nozzle; 4 — oxygen bottles.

Reactive Pistol

The Garrett company has designed, under NASA contract, a reactive pistol (Zip) for maneuvering in space.

The reactive pistol (Figure 6.9) consists of a handle in the upper portion of which there is mounted a nozzle directed forward, and two tubes 405 mm long, terminating in nozzles directed aft run to both sides. The handle is equipped with a rocker-type trigger. In order to maneuver in space, the cosmonaut must hold the pistol at the center of gravity of his body and depress the upper or lower trigger arm, as a result of which he moves forward or backward. The thrust developed by the pistol is 0.9 kG.

The reactive pistol uses gaseous oxygen as the working fluid. The 308 gram oxygen supply is stored in two bottles at 280 kG/cm^2 pressure.

A camera is mounted on the pistol. The total weight of the pistol and camera is 3.4 kG, the total impulse is 18 kG/sec.

The pistol is shown schematically in Figure 6.10 [5].

The reactive pistol was later altered considerably for carrying out flights on the Gemini-8 spacecraft. The working fluid used to create the reactive thrust was Freon 14, stored in the backpack; the total impulse developed by the Freon was 270 kG/sec.

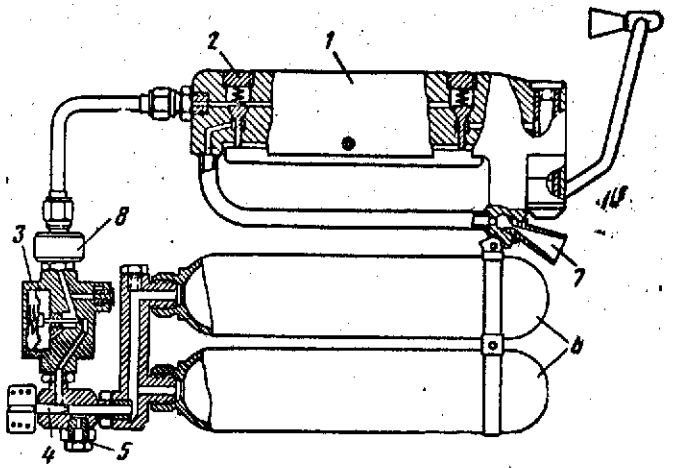


Figure 6.10. Pistol for maneuvering in space.
1 — pistol handle; 2 — thrust regulator; 3 — pressure regulator; 4 — gas flow valve; 5 — filler; 6 — bottles; 7 — nozzle; 8 — coupling.

During the flight of Gemini-9, compressed nitrogen stored aboard the vehicle was used for pistol operation. Nitrogen supply to the pistol was provided through a hose attached to the tether (Figure 6.11).

AMU

A pack-type AMU has been developed in the USA under contract with the Air Force (Figure 6.12) for space maneuvering.

The AMU operates in conjunction with the LSS located in a chest pack.

The system must provide movement in all directions and stabilization of the astronaut's attitude.

Commands are transmitted from the astronaut's hand by means of levers located on special brackets. To obtain forward movement, the lever is also moved forward, or correspondingly

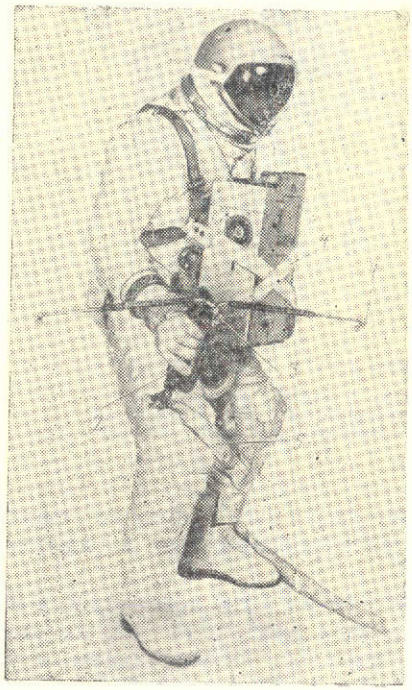


Figure 6.11. Jet pistol and life support system used in the Gemini-9 spacecraft.

1 — jet pistol thruster; 2 — jet pistol; 3 — jet nozzle for aft movement; 4 — life support system pack; 5 — hose feeding fuel to pistol.

Figure 6.12. AMU mounted on Gemini-9 spacecraft astronaut.

1 — life support system pack; 2 — space maneuvering unit; 3 — lanyard connecting astronaut with vehicle; 4 — control levers.

backward when backward movement is required.

The position of the astronaut in space is maintained by three gyros. Automatic stabilization is deactivated when switching to manual control.

All the vitally important systems are duplicated. When a problem arises in the primary system, a corresponding signal is sent to activate the backup system. /214

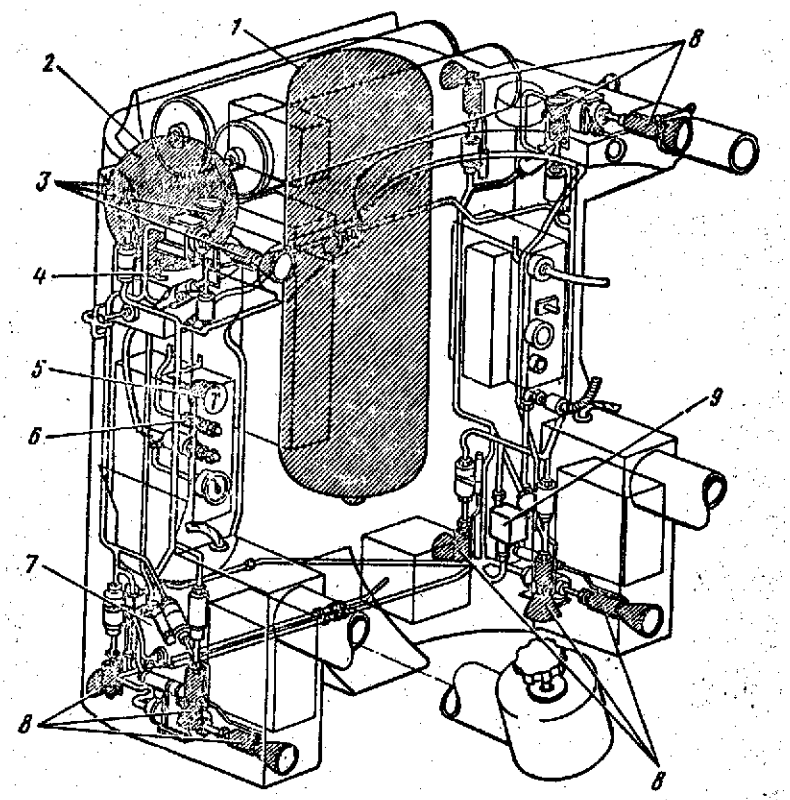


Figure 6.13. AMU propulsion system.

1 — hydrogen peroxide fuel tank; 2 — nitrogen bottle; 3, 8 — thrustors; 4 — nitrogen valve; 5 — nitrogen pressure gage; 6 — nitrogen filler; 7 — backup system valve; 9 — main system valve.

AMU weight is about 75 kg. The LSS weighs about 20 kg. The weight of the astronaut fully outfitted (including his pressure suit) is about 185 kg [5].

We can identify the following basic systems in the AMU: propulsive, control, oxygen, electric power, warning, and communication.

Propulsive system. The fuel is 90% hydrogen peroxide (H_2O_2). The 10.8 kG hydrogen peroxide supply is stored in a tank. The total impulse developed by the system is about 1350 kG/sec. The

primary elements of the propulsive system are shown in Figure 6.13. The hydrogen peroxide is contained in a rubber chamber which is, in turn, installed in a tank. Nitrogen stored in a bottle under 210 kG/cm^2 pressure is used to feed the fuel to the thrusters.

Fuel flow is regulated manually. Two thrusters provide forward thrust, two provide aft thrust, two are used for upward movement, and two for downward movement. The nominal thrust of each thruster is one kilogram.

The thrusters which create thrust for fore and aft movement are used in various combinations to provide control in heading and pitch. The thrusters which provide thrust for up and down /215
movement provide displacement in the vertical plane and control of the bank angle.

The control system permits the astronaut to displace in three planes and stabilizes his attitude. The system operates automatically and manually (Figure 6.14).

The oxygen system is located in the backpack. The 3.1 kG oxygen supply is stored in a bottle under 525 kG/cm^2 pressure. A reducing valve reduces the oxygen pressure to 6.8 kG/cm^2.

An emergency oxygen supply in the chest pack is intended for*

The electrical system is powered by a silver zinc battery. This system is also completely duplicated. Actually, two independent batteries operate in a single case.

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*[Translator's Note. Balance of statement omitted in original foreign text.]

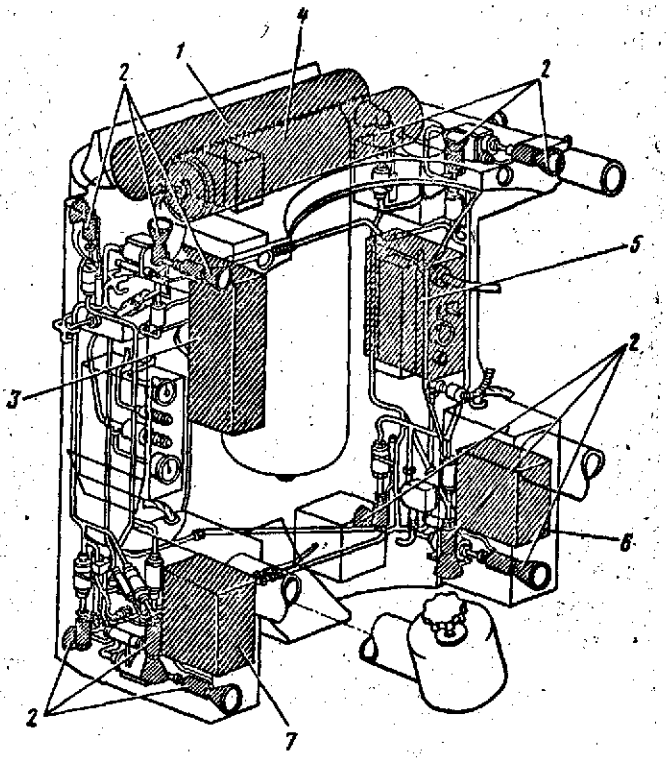

Figure 6.14. AMU control system.

1 — backup system electric power source; 2 — thrusters; 3 — backup system electronics; 4 — main system electric power source; 5 — main system electronics; 6 — main system gyros; 7 — backup system gyros.

The warning system provides for the transmission of a warning signal in case of failure of any system. The critical parameters are: low pressure in the fuel tank, oxygen pressure decrease, low fuel supply. In case of any of these problems in the control system, an audio signal is sent to the earphones or a lamp illuminates on the control panel located on the astronaut's chest.

The communication system provides for transmission of /216
telemetry measurement information to the spacecraft and two-way communications.

4. Extravehicular Space Suits

Space Suit of Cosmonaut A. A. Leonov

The outfit in which Leonov walked in space included a pressure suit, backpack, and tether with which the cosmonaut was connected with the spacecraft (see Figures 6.1 and 6.15).

The pressure suit shell is a packet consisting of the restraint shell and two hermetic (main and reserve) shells.

The helmet of Leonov's pressure suit consists of the shell, tilting visor, and light filter. The shell is made of an aluminum alloy. The double visor is made of organic glass. The visor can be raised manually. Raising and lowering the light filter is accomplished by rotating the corresponding handle. The helmet is restrained by a lock. The helmet dimensions do not restrict rotation of the head.

The pack includes: oxygen supply, oxygen regulator, and remote control. The pack is attached on the back by means of a quick-acting disconnect.

The oxygen regulator provides pure oxygen flow into the suit helmet for breathing, and into the suit shell for ventilation. The oxygen flowrate varies with altitude. /217

The pressure suit system includes: pressure suit itself, outer garment, communications helmet, boots, underwear, and other components.

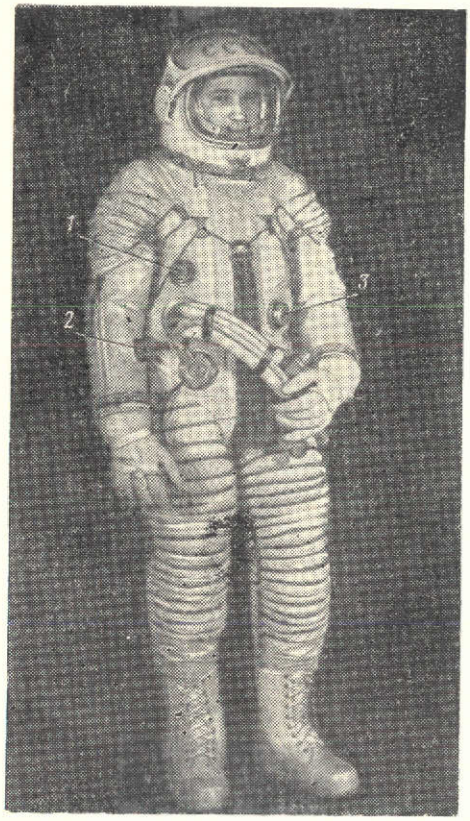

Figure 6.15. Pressure suit of A. A. Leonov without outer garment.

1 — safety valve; 2 — pressure gage; 3 — pressure regulator.

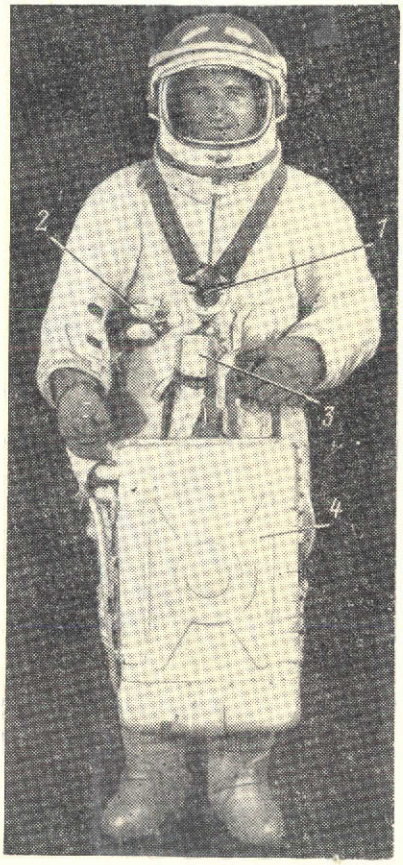

Figure 6.16. Pressure suit for Soyuz spacecraft with autonomous life support system.

1 — attachment strap lock; 2 — single point connector; 3 — remote control; 4 — life support system pack.

Soyuz Spacecraft Pressure Suit

The pressure suit of the Soyuz spacecraft was designed for spacewalking (Figure 6.16). The pressure suit is used in conjunction with a regenerative LSS. It operates in two modes.

Oxygen circulation in the suit is provided by a centrifugal blower. Electric power is provided from the spacecraft through

an umbilical. Provision is made for emergency oxygen supply from a bottle.

The pressure suit consists of an outer garment, made of lavsan fabric, kapron restraint garment, two hermetic shells, ventilated garment, removable helmet, and gloves. The pressure suit helmet is equipped with tilting visor and light filter.

G-4C Pressure Suit

E. White was the first American astronaut to go out into space from the hatch of the Gemini-4 satellite spacecraft on 3 June 1965. White was connected to the ship by a nylon tether about seven meters long, including an umbilical through which breathing and suit ventilation oxygen was supplied from the ship (about 60 liters/minute), communications leads, and biomedical data transmission leads. The total weight of the tether was about 4 kG.

A chest pack included the oxygen flow control system and emergency oxygen supply (see Figure 4.2). White held in his right hand a pistol with camera mounted on it (Figure 6.17).

As mentioned previously, the G-4C spacecraft commander's pressure suit differed from the G-3C suit in the presence of vacuum-barrier insulation, meteoroid garment, and a special light filter (Figure 6.18). In this connection, the weight of the G-4C pressure suit system increased to 14,4 kG.

The VBTI is made of seven layers of aluminized mylar film. The meteoroid garment is made of rubberized nylon.

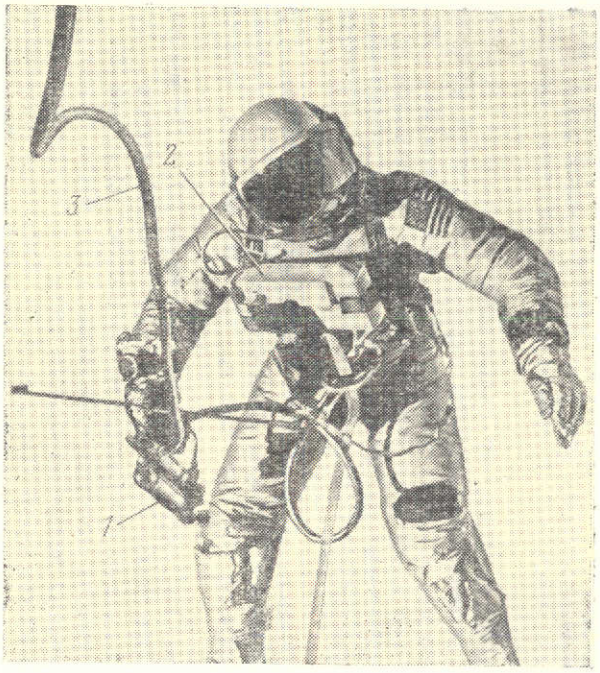

Figure 6.17. Astronaut E White in space.

1 — jet pistol; 2 — life support system; 3 — tether connecting astronaut with vehicle.

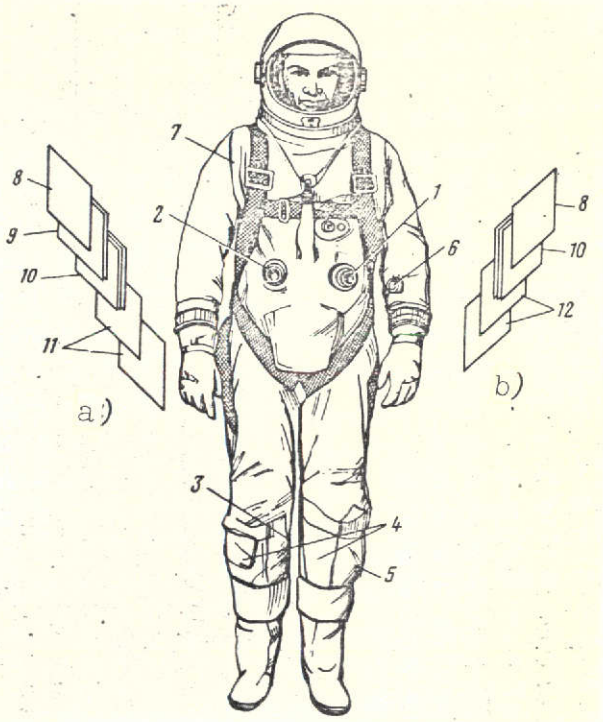

Figure 6.18. G-4C pressure suit [5].

a — arrangement of layers in pressure suit for flight aboard Gemini-4; b — arrangement of layers in pressure suit for flight aboard Gemini-8; 1 — oxygen inlet fitting; 2 — fitting for gas discharge from suit; 3 — knife pocket; 4 — pockets with flight cards; 5 — pocket for scissors; 6 — pressure gage; 7 — pocket for neck sealing collar; 8 — outer garment of NG-1 nylon; 9 — anti-meteorite layer (NG-1 nylon); 10 — VBTI; 11 — nylon anti-meteorite layer; 12 — rubberized nylon anti-meteorite layer.

The pressure suit helmet is rotatable, the light filter is located on the outside. The visor lifts up and is made of polycarbonate. The boots are made of the same fabric as the outer garment (see Figure 6.12).

A pressure of 207 — 186 mm Hg (corresponding to an altitude of 9500 — 1050 m) or 0.273 — 0.245 kG/cm^2 is maintained in the G-4C pressure suit. At this pressure the gas leakage from the pressure suit does not exceed 0.2 liters/minute [8].

A LSS of the ventilation type with forced oxygen circulation provided by an injector (see Figure 4.3) was used in the later Gemini-8 flight. Oxygen was supplied from on board and some (3.2 kG) was located in the backpack. The tether length was increased to 38 meters.

For flights aboard the Gemini-9 spacecraft, the G-4C suit was modified by introducing fireproof fabric on the legs to protect against the high temperatures during operation of the AMU system reactive thrusters (see Figure 6.13).

REFERENCES

1. Kutateladze, S. S. and V. M. Borishanskiy. Spravochnik po teploperedache (Heat Transfer Handbook), Gosenergoizdat, Moscow, 1959. /219

2. Kaganer, M. G. Teplovaya izolyatsiya v tekhnike nizkikh temperatur (Thermal Insulation in Low-Temperature Engineering), Mashinostroyeniye, Moscow, 1966.

3. Al'tshuller, L. V. "Shock Waves in Solids," Uspekhi fizicheskikh nauk, Vol. 85, No. 2, 1965.

4. Andriankin, E. I. and Yu. S. Stepanov. "On Penetration Depth during Meteorite Impact," Iskusstvennyye sputniki zemli, Press of the Academy of Sciences USSR, Vol. 15, Moscow, 1963.

5. Gemini summary conference, NASA, February 1 — 2, 1967.

6. Wand, D. I. J. Multiple Layer Insulations for Aerodynamically Heated Structures. Peter F. Glaser, 1962.

7. Monroe, G. M. and W. C. McMillin. Description of the Astronaut Maneuvering Unit. Report presented at 17th Astronautic Congress, Madrid, September (sic), 1962.

8. Johnston, R. C. and E. L. Hays. The Development and Operation of Extravehicular Equipment. Report presented at 17th Congress of Bioastronautics, Vol. 9, Madrid, 1966.

9. Isayev, S. I., et al. Osnovy termodinamiki, gazovoy dinamiki, i teploperedachi (Fundamentals of Thermodynamics, Gasdynamics, and Heat Transfer), Mashinostroyeniye, Moscow, 1968.

10. Drachev, N. M., V. N. Morozkin, and I. N. Potapov. Study of Small High-Velocity Particle Penetration in Various Materials, Inzhenerno-fizicheskiy zhurnal, Vol. 22, No. 3, 1972.

11. AIAA Paper No. 70-851.

CHAPTER 7
PRESSURE SUIT FOR LUNAR EXPLORER

1. General Information

Development of the first model of the pressure suit for /220
the lunar cosmonaut-explorer was preceded by flights of spacecraft used to study the Moon without landing on its surface and a whole series of reserach investigations conducted to analyze the behavior of man under conditions similar to those on the Moon.

The results of these studies made it possible to formulate the following specific requirements which must be satisfied in developing the pressure suit for exploring the Moon:

— possibility of cosmonaut moving about on his own over the lunar surface with account for its relief and the possibility of regaining one's feet in case of a fall;

— possibility of carrying out scientific observations (working with instruments, collecting lunar rock samples, primitive drilling);

— possibility of contact with lunar surface having temperatures from -130 to +160° C;

— possibility of raising and lowering the light filter using one hand;

— possibility of taking liquid foods and disposing of liquid wastes (urine);

— maintain normal temperature conditions in the pressure suit with account for the temperature variations characteristic of the lunar surface;

— protection against damage in case of collision with meteoric matter (primary and secondary);

— protect the eyes against the harmful effects of solar radiation and IR radiation of the heated lunar surface.

The requirements for the autonomous life support systems were presented in Chapter 4.

We shall present the justifications for the abovementioned pressure suit requirements.

2. Kinematics of Cosmonaut Movement on the Moon

Egress of man onto the Moon is associated, first of all, with the necessity for independent locomotion under conditions of low gravity in comparison with that on the Earth (acceleration one-sixth "g" or 0.165 g).

Special studies of man's movement under reduced gravity force under Earth-based conditions were necessary in order to find a rational solution of this problem. Airplanes, flying laboratories, and various stands were used to simulate such conditions. However, none of these devices can create conditions which are entirely identical to those on the Moon.

Reduced gravity can be created for 20 — 30 seconds aboard /221
an airplane. However, it is not possible to perform the required studies during this time period. Devices with submersion of the subject in water exert a stabilizing action and hinder the movement of the extremities because of hydrostatic pressure.

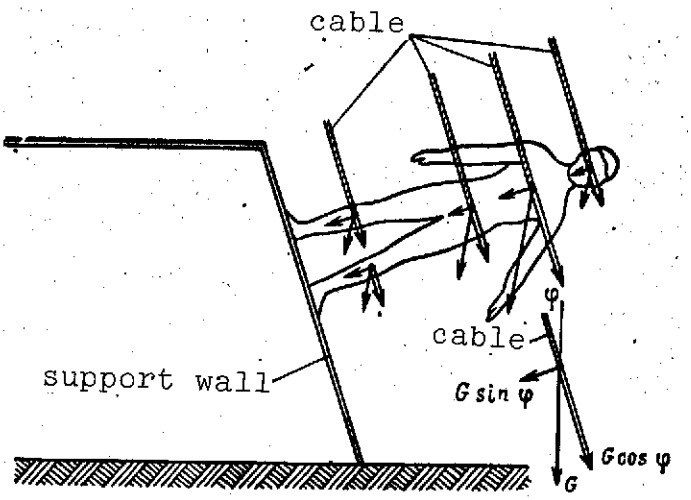

Figure 7.1. Stand for studying on the Earth cosmonaut movement under conditions corresponding to the gravity force on the Moon. G is body weight.

Special stands with a system of cables on which the subject is suspended in order to reduce the pressure of his weight on the supporting surface also have a marked influence on limb movement kinetics.

Figures 7.1 and 7.2 show a stand for studying human movement kinetics. The inclination of the cables on which the subject is supported is selected so that his weight component is equal to 0.166 times his Earth weight. Under this condition, it is obvious that

$$\sin\varphi=\frac{g_m}{g_e}=0{,}165 \quad \text{and} \quad \varphi=9°30',$$

where g_m and g_e are the gravity force accelerations on the Moon and Earth.

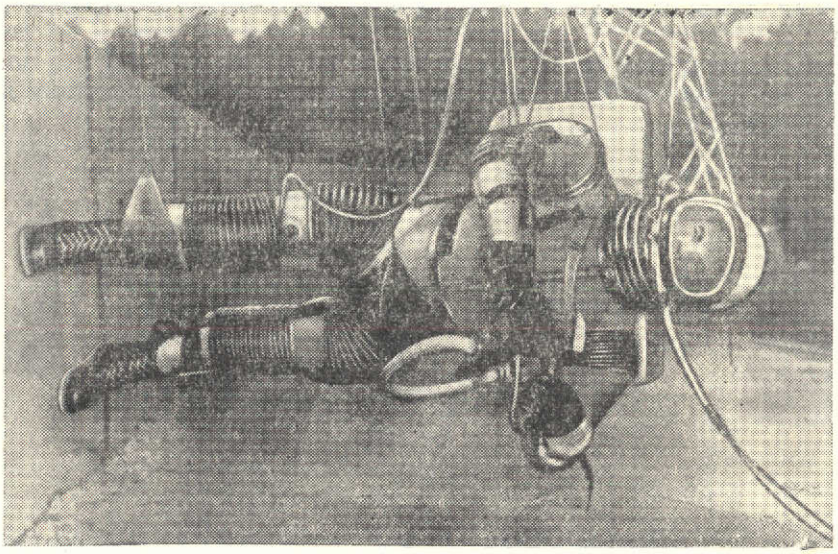

Figure 7.2. General view of stand (Aviation Week, Vol. 85, No. 7, August 15, 1966).

Studies made by Bogdanov, Gurfinkel, and Panfilov* showed that, in the case of gravity force reduction, man's habitual posture when he stands and moves under Earth conditions is changed. Specifically, the posture shown in Figure 7.3 is characteristic for man on the Moon.

The experimental data shown in Table 7.1 can yield an idea of the mobility of a man in a pressure suit.

The intensity of man's movement is best evaluated by comparing the energy expenditures when traveling a definite distance. Table 7.2 shows some data on such expenditures when walking along a horizontal surface.

Walking along an inclined surface has also been the subject of many investigations and some results are shown in Figure 7.4.

*Biofizika, Vol. 15, No. 1, 1969.

TABLE 7.1

SOME CHARACTERISTICS OF MAN'S MOBILITY IN A PRESSURE SUIT WITH VARYING DIFFERENTIAL PRESSURE IN THE SUIT AND VARIOUS GRAVITY FORCE MAGNITUDES [3] (FROM RESULTS OF STAND TESTS)

Gravity force	Suit pressure kG/cm^2	Vertical jump cm	Horizontal jump cm
1	0	52	165
	0.245	30.5	101
1/6	0	235	366
	0.245	140	213

TABLE 7.2

ENERGY EXPENDITURES OF MAN WALKING ON A HORIZONTAL SURFACE WITH VARYING LOAD (MAN'S WEIGHT ABOUT 70 kg, WEIGHT OF CLOTHING AND INSTRUMENTS 9 kg [3])

Soil nature	Velocity km/hr	Energy expenditure kcal/min
Hard surface	5.5	5.5
Grass	5.6	6.3
Plowed field	5.4	7.0
Packed snow	3.8	11.9
Loose snow	4.0	20

The maximum power and energy expenditures of man when performing work are illustrated by the curves in Figure 7.5.

The curve segment which is nearly horizontal is equal to the period of time from 5 minutes to 50 minutes and indicates that highly trained individuals are capable of developing comparatively large power (about 0.5 hp). We note that this level /222

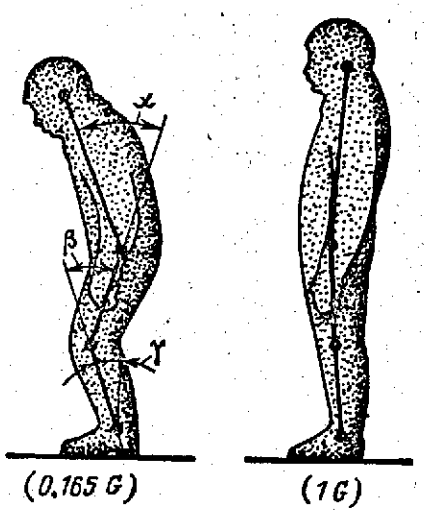

Figure 7.3. Posture of man standing on the Moon (0.165 g) and on the Earth (1 g) (α = 16 ± 1°; β = 12 ± 1°; γ = 5 ± 1°).

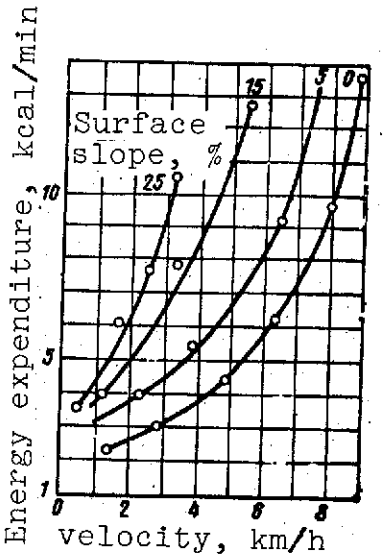

Figure 7.4. Energy expenditure of man walking on inclined plane at different speeds [3].

is far above that which cosmonauts with average physical preparation can maintain.

Under reduced gravity force conditions, the energy expenditures when walking are considerably lower than under Earth conditions and depend to a considerable degree on the structural characteristics of the pressure suit [10].

Measurements made during Neil Armstrong's stay on the Moon /224
(crew of the Apollo 11 spacecraft) showed that the energy expenditures did not exceed 250 — 340 kcal/hr.*

A preliminary evaluation of pressure suits intended for movement on the Moon can be made after measuring their mobility (positions 1 — 6) and energy expenditures (positions 9 — 11) while performing the complex of motions shown in Figure 7.6.

*N. Armstrong, Study of the Lunar Surface, report to COSPAR meeting, 1970.

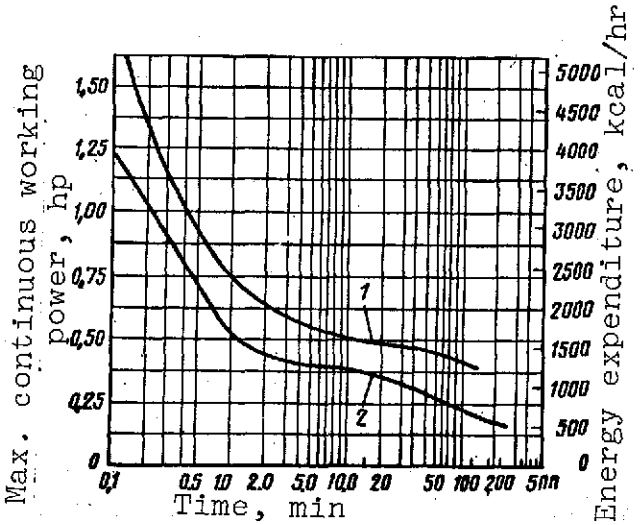

Figure 7.5. Maximum power and energy expenditure of man when performing work [3].

1 — with conditioning; 2 — without conditioning.

3. Heat Exchange between Cosmonaut and Surrounding Medium under Lunar Surface Conditions

The lunar surface temperature changes in time with change of the solar ray incidence angle. Calculations have shown that the maximum temperature reaches +126° C, the minimum reaches -153° C.

The temperature on the lunar surface was determined from the formula

$$T_m = \sqrt[4]{\frac{A_s q_0 \cos\varphi}{\varepsilon_m \sigma_0}}, \qquad (7.1)$$

where A_s is the coefficient of solar ray absorption by the lunar surface, q_0 — the solar constant on the lunar surface (q_0 = 1200 kcal/(m²/hr)); φ — the angle of solar ray incidence on the lunar surface; ε — the lunar surface emissivity; σ_0 — the

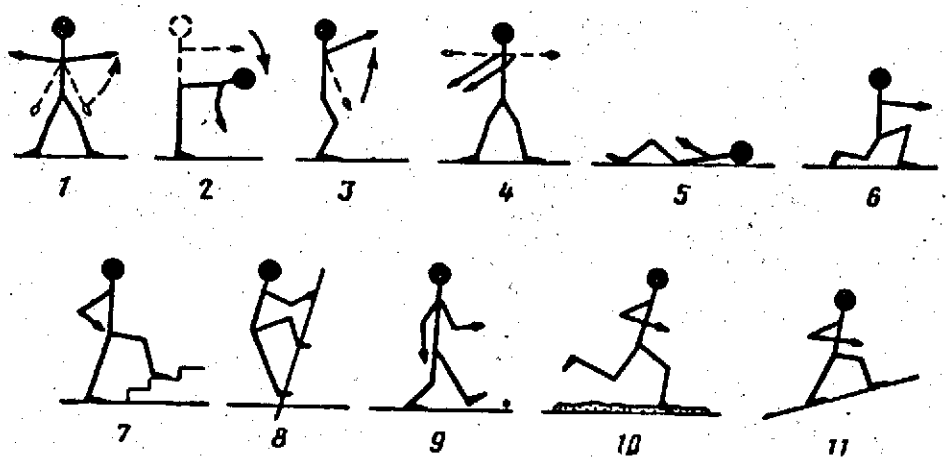

Figure 7.6. Typical complex of motions used for comparative evaluation of human mobility in a pressure suit.

1 — 11: various forms of movement.

Stefan Boltzmann constant (σ_0 = 4.88kcal/(m^2/hr/K^4)).

As a result of thermal radiation into cosmic space, the lunar surface temperature falls rapidly at night and approaches a constant magnitude determined by the as-yet-unknown thermal influx from the deep-lying lunar soil layers.

The curve shown in Figure 7.7b shows the daily (28 Earth days) lunar surface temperature variation from astronomical observation data.

Under lunar daytime conditions, the heat exchange between the cosmonaut and the medium surrounding him is made up of the following thermal fluxes (Figure 7.7a):

— Q_s is the amount of heat received by the cosmonaut as a result of direct solar radiation absorption by the pressure suit;

— Q_c is the amount of heat received by the cosmonaut as a result of his footwear contacting the lunar surface;

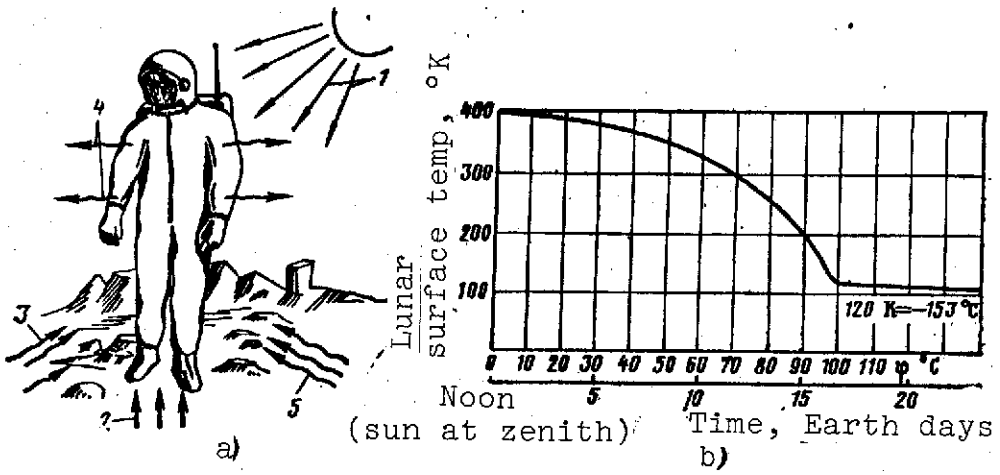

Figure 7.7. Heat exchange between cosmonaut and medium on lunar surface under lunar daytime conditions.

a — heat flux scheme; b — lunar surface temperature versus solar radiation incidence angle φ; 1 — heat flux from Sun; 2 — heat flux in case of direct contact with lunar surface; 3 — thermal radiation of heated lunar surface; 4 — heat radiated by man through pressure suit into the medium; 5 — solar radiation heat reflected by lunar surface.

— Q_m is the amount of heat received by the cosmonaut /225 through the pressure suit as a result of solar radiation reflection by the lunar surface;

— Q_{ref} is the amount of heat obtained by the cosmonaut through the pressure suit from thermal radiation of the lunar surface;

— Q_{rad} is the amount of heat radiated by the cosmonaut into the surrounding medium through the pressure suit surface.

The heat flux Q_c is of local importance and is considered only in calculating footwear thermal insulation. Because of the low lunar surface reflectivity, the thermal flux Q_c is comparatively small and is not considered in the overall pressure suit heat balance.

The hourly heat influx because of pressure suit absorption of direct solar radiation

$$Q_s = S_m A_{s\,su}\, q_0 \sin\varphi, \qquad (7.2)$$

where S_M is the area of the pressure suit surface projection on a plane perpendicular to the direction of solar ray incidence; $A_{s\ su}$ is the coefficient of solar energy absorption for the pressure suit outer surface.

The lunar thermal self-radiation received by the pressure suit is

$$Q_m = 0{,}5\varepsilon_{su}\sigma_0 S T_m^4, \qquad (7.3)$$

where ε_{su} is the pressure suit outer surface emissivity; 0.5 is the coefficient of mutual irradiation (for a vertical cylinder on a horizontal plane); S is the total pressure suit surface area.

The variation of the heat flux $Q_s + Q_m$ as a function of solar ray incidence angle for different constant absorption coefficient $A_{s\ su}$ values and constant coefficient $\varepsilon_{su} = 0.9$ is shown in Figure 7.8. These curves apply to the worst case (design case) when the pressure suit surface is covered with lunar dust ($\varepsilon = 0.9$).

In the calculations, the angle φ was limited to the range $0° — 60°$.

The amount of heat radiated by the suit surface is

$$Q_{rad} = \varepsilon_{su}\sigma_0 S T_1^4, \qquad (7.4)$$

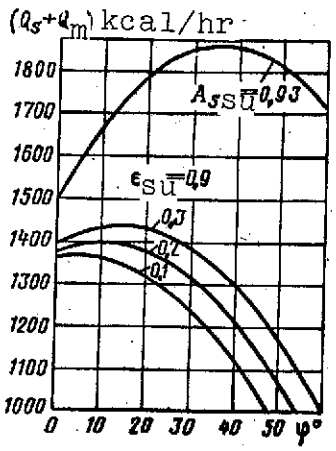

Figure 7.8. Typical variation of heat flux (Q_s + Q_m) received by cosmonaut through pressure suit as function of solar ray incidence angle for various constant values of the absorption coefficient $A_{s\ su}$.

where S is the suit radiating surface area, T_1 — the suit outer surface equilibrium temperature in K.

The heat balance equation /226
for the suit outer surface can be written as

$$Q_{1-2}=Q_s+Q_m-\varepsilon\sigma_0 S T_1^4. \qquad (7.5)$$

The temperature T_1 of the suit outer surface can be determined from this equation.

To determine the thermal flux penetrating to the body, the suit shell of complex form is replaced by a system of equivalent cylindrical shells with the magnitude of the ventilation gap assumed constant (Figure 7.9).

In the calculation, we usually specify:

— the thermal resistance of the VBTI and underwear (the thermal resistance of the suit shell is not considered in the calculation);

— the dimension of the ventilation gap;

— the air velocity in the ventilation gap;

— the air temperature at the inlet to and outlet from the suit.

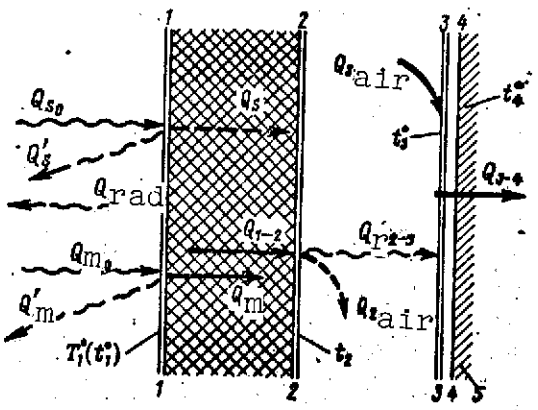

Figure 7.9. Scheme for computing thermal fluxes in suit. 1 - 2 — suit packet; 2 - 3 — ventilation gap; 3 - 4 — underwear; 5 — surface of man's body; Q_s — thermal flux from direct solar radiation received by the pressure suit; Q_{s_0} — solar radiation energy; Q_{m_0} — thermal flux from heated lunar surface; Q_{rad} — heat radiated by pressure suit surface; Q_m — heat flux from lunar radiation received by the pressure suit; Q_{1-2} — heat flux penetrating to surface 2; $Q_{2_{air}}$ — heat received by ventilating air from surface 2; $Q_{r_{2-3}}$ — radiative heat flux from surface 2 to surface 3; $Q_{3_{air}}$ — heat given up by ventilating air to surface 3; Q_{3-4} — heat flux passing through shell 3 to man's body and received by the pressure suit cooling system along with the heat emitted by the man; Q'_s — reflected solar energy; Q'_m — reflected lunar thermal radiation energy; t_1 — t_4 — surface temperature in °C.

In the general case, the heat flux Q_{1-2} is found from the formula /227

$$Q_{1-2}=\frac{\lambda_1}{\delta_1}S_{\text{av }1-2}(t_1-t_2), \tag{7.6}$$

where λ_1 is the thermal conductivity of the pressure suit outer shell material in kcal/(m/hr/°C); δ_1 — the thickness of the pressure suit outer shell (suit packet) 1 — 2 in meters; t_2 —

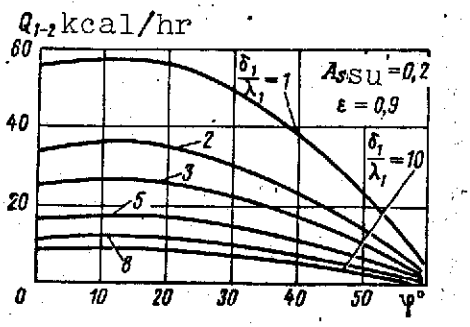

Figure 7.10. Typical amount of heat Q_{1-2} penetrating into the pressure suit through the VBTI; for different VBTI thermal resistance as function of Sun position.

δ_1/λ_1 — VBTI thermal resistance; φ — angle of Sun ray incidence on pressure suit surface.

the temperature of surface 2 in °C; $S_{av\ 1-2}$ — the average area of the outer cylindrical shell 1-2 in m^2,

$$S_{av\ 1-2} = (S_1 + S_2)/2.$$

Since the pressure suit packet thickness is relatively small, we can assume that $S_1 = S_2 = S_{av\ 1-2}$.

The variation of the heat flux Q_{1-2} penetrating the pressure suit for different VBTI thermal resistance as a function of Sun position is shown in Figure 7.10.

The amount of heat removed by the ventilation air from surface 2 (see Figure 7.9) per unit time is

$$Q_{2air}=\alpha_2 S_2(t_{in}-t_{out}), \qquad (7.7)$$

where α_2 is the coefficient of heat transfer from surface 2 to the air in kcal/m^2/hr/K; S_2 — the area of surface 2 in m^2; T_{in} — the air temperature at the suit inlet in °C; T_{out} — air temperature at suit outlet in °C.

The radiational heat flux between surfaces 2 and 3 is

$$Q_{r\,2-3}=\alpha_r S_3(t_2-t_3), \qquad (7.8)$$

where α_r is the effective coefficient of heat transfer by radiation in kcal/m^2/hr/°C; S_3 — the area of surface 3 in m^2; t_2 — the temperature of surface 2 in °C; t_3 — the temperature of surface 3 in °C.

In (7.8), the radiative heat transfer coefficient

$$\alpha_r \approx 0{,}04 \varepsilon_{ef} \sigma_0 \left(\frac{T_m}{100}\right)^3, \qquad (7.9)$$

where $T = (T_2 + T_3)/2$ (T_2 and T_3 are the temperatures of surfaces 2 and 3 in K); $\sigma_0 = 4.9$ kcal/m^2/hr/K^4 is the blackbody radiation coefficient; ε_{ef} is the effective emissivity of the system consisting of surfaces 2 and 3, found from the formula /228

$$\varepsilon_{ef} = \frac{1}{1/\varepsilon_3 + S_3/S_2 \left(\frac{1}{\varepsilon_2} - 1\right)}, \qquad (7.10)$$

where ε_2 and ε_3 are the emissivities of surfaces 2 and 3.

The amount of heat removed by the ventilating air from surface 3 per unit time is

$$Q_{air} = \alpha_3 S_3 (t'_{air} - t_3), \qquad (7.11)$$

where α_3 is the coefficient of heat transfer from the air to surface 3 in kcal/m^2/hr/°C.

The heat flux penetrating through surface 3 to the body of the wearer is

$$Q_{3-4} = \frac{\lambda_3}{\delta_3} S_{av\ 3-4} (t_3 - t_4), \qquad (7.12)$$

where λ_3 is the thermal conductivity of shell 3 (underwear) in (m^2/hr/°C/Kcal; $S_{av\ 3-4}$ — the average area between surfaces 3 and 4 in m^2; t_4 — the temperature of the wearer's body surface 4 in °C.

Since the underwear thickness is small, we can take $S_4 = S_3$.

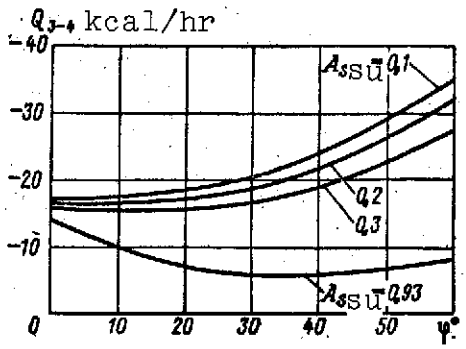

Figure 7.11. Thermal flux Q_{3-4} penetrating through shell 4 to man's body as function of Sun position (angle φ) for various values of outer shell absorptivity $A_{s\ su}$. (Curves were calculated for emissivity ε = 0.9, ventilation air flow-rate 150 liters(s)/min, and pressure suit shell packet thermal resistance δ_1/λ_1 = 5 m^2/hr/°C)/kcal.

Figure 7.11 shows the calculated dependence of the heat flux penetrating through the underwear to the wearer's body (Q_{3-4}) on Sun position (angle φ) for various values of the outer shell absorptivity ($A_{s\ su}$). We note that, in the dependence on Sun position, the magnitude of the irradiated surface changes, and therefore the amount of heat penetrating into the pressure suit varies.

We see from the pressure suit heat balance diagram shown in Figure 7.12 that the major portion of the heat flux is that radiated by the pressure suit and the smaller part is that removed by the ventilating air. The remainder of the heat must be removed by sweat evaporation or use of a liquid cooled garment.

4. Systems for Cooling Man in a Pressure Suit

The performance of various sorts of work on the surface of the Moon involves large energy expenditures and corresponding evolution of heat by the individual. This is explained by the effort which the wearer must expend in overcoming the resistances in the pressure suit hinges. Moreover, a considerable amount of heat will penetrate into the pressure suit shell from the outside in spite of its high thermal resistance. /229

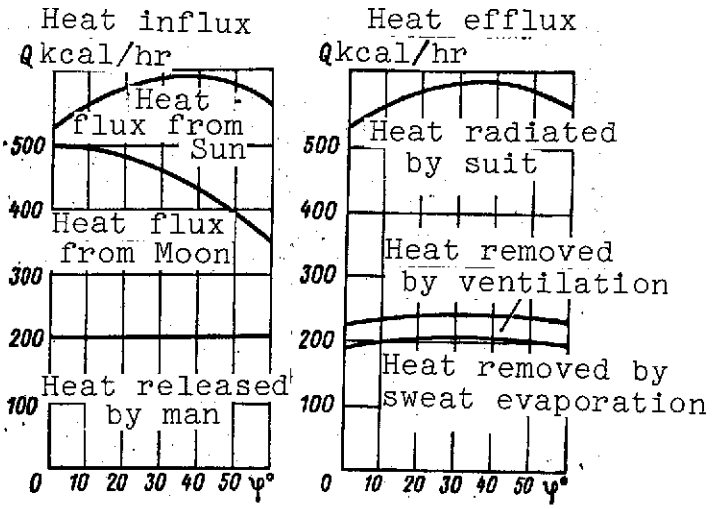

Figure 7.12. Heat balance of man in pressure suit on lunar surface. (In the calculations, we took: $A_{s\ su} = 0.2$; $\varepsilon = 0.2$, air flowrate 150 liters(s)/min, thermal resistance 3(m^2/hr/°C)/kcal.)

Heat removal by evaporation of a large amount of sweat may lead to dehydration of the organism and involves significant stressing of man's thermal temperature regulation system.

Cooling of the pressure suit by increasing the amount of ventilation air is not possible in practice because of the associated considerable energy expenditure increase. More rational is the use of a liquid (water) cooled garment (LCG) or an evaporative cooling system.

Liquid Cooled Garment

Tests have shown that, with proper heat removal organization, the LCG or WCG [water cooled garment] can remove 450 to 650 kcal/hr of heat.

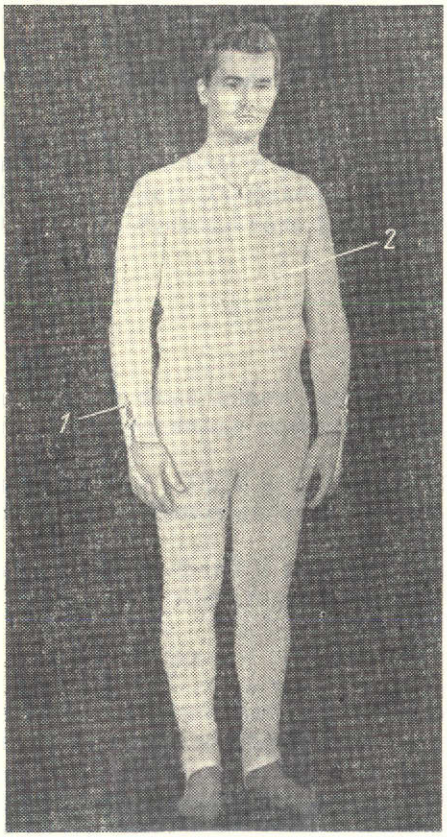

Figure 7.13. Liquid cooled garment.

1 — lacing for fitting garment to individual; 2 — opening for donning garment.

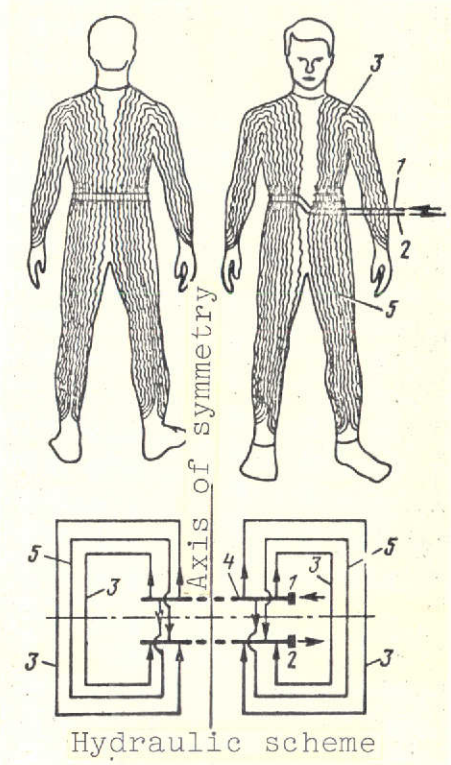

Figure 7.14. Possible arrangement of liquid cooled garment tubes (variant 1).

1 — water in; 2 — water out of garment; 3, 5 — coolant tubes; 4 — header.

The basic requirements imposed on the LCG are operating reliability, lowest possible hydraulic resistance, and minimum weight.

Moreover, the garment must be easily donned and doffed, must not restrict wearer movement, and must be constructionally compatible with the other pressure suit elements.

The LCG consists of a coverall and a system of tubes through which the coolant circulates (Figures 7.13 and 7.14).

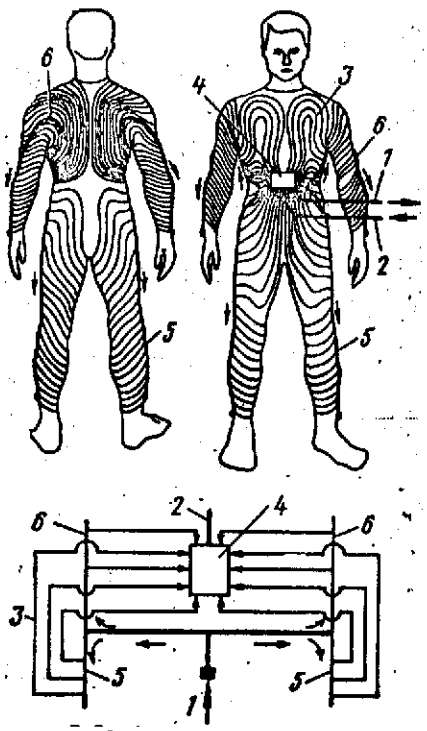

Figure 7.15. Possible arrangement of liquid cooled suit tubes (variant 2).

1 — header for water feed to garment; 2 — water return; 3 — tubes; 4 — return water header; 5 — hose supplying leg cooling water; 6 — hose supplying arm cooling water.

The coverall is made of tricot weave fabric and has a zippered opening for donning and doffing. Lacing is used to fit the coverall in girth.

The LCG tubes are made from flexible tubing with inside diameter from 1.5 to 3 mm and wall thickness 0.5 — 1 mm. These tubes are made of polymer materials. Polyvinyl chloride tubes have adequate strength, thermal stability, elasticity, and bond well. The number (20 — 80) of tubes depends on the design. The total tube length is 80 — 120 m.

Figure 7.14 shows a possible LCG tube arrangement. The liquid entering the header 4 is distributed upward through tubes along the chest and back. The liquid flows downward through the tubes 5 and, after making a turn in the vicinity of the ankle, flows back upward. In all, there are 40 tubes. The disconnect fitting is equipped with a check valve so that liquid is not spilled when disconnecting the garment from the supply line.

Figure 7.15 shows a different LCG tube arrangement in which the entering liquid is supplied to the limbs and is then distributed through tubes and collected in the header 4.

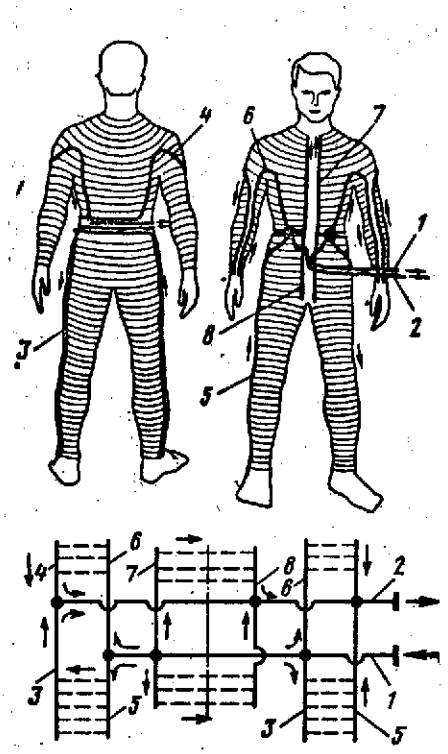

Figure 7.16. Possible arrangement of liquid cooled suit tubes (variant 3).

1 — water in; 2 — water out; 3 — manifold for water supply to legs; 4 — manifold for water supply to arms; 5 — manifold for water from legs; 6 — manifold for water from arms; 7 — manifold for water to trunk; 8 — manifold for water from trunk.

Still another LCG variant is shown in Figure 7.16. In this garment, the liquid supply and collection manifolds are located along the arms and legs.

Connection of the tubes with the manifold can be made by bonding (Figure 7.17) or with the aid of a special metal adapter (Figure 7.18). The connection using the adapter is more reliable since quality control of the bonded seam is very difficult.

The garment weighs (depending on the tube arrangement used) 1.8 — 2.5 kG (coverall 1 — 1.3 kG, tubes 0.5 — 0.7 kG, manifold 0.2 — 0.4 kG, disconnects 0.1 kG). /230

The coolant used is usually water, however use of other liquids with lower freezing point is possible.

The minimum acceptable water temperature at the garment inlet depends to a considerable degree on the subjective characteristics of man. When wearing the garment directly on the body (without underwear), the entering water temperature should be 14 — 16° C. When wearing the garment over underwear, this temperature can be reduced to 10 — 12° C.

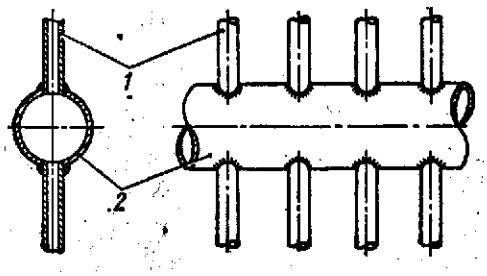

Figure 7.17. Welding of tubes to manifold.

1 — tube; 2 — manifold.

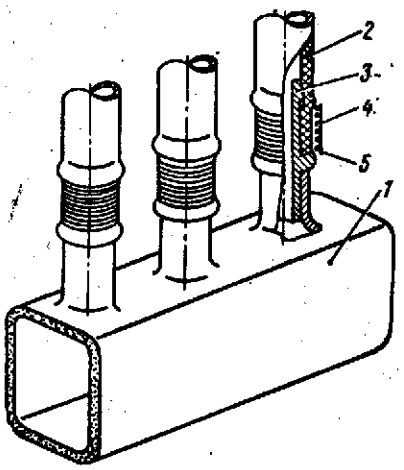

Figure 7.18. Tube connection with manifold.

1 — manifold; 2 — tube; 3 — adapter; 4 — wrapping with strong cord; 5 — protective covering (tape).

Heat transfer from the body to the water circulating in the tubes is a process which has received very little study, and all forms of heat transfer take place in a complex interaction in this process (Figure 7.19):

— conductive heat exchange with direct contact of the tubes with the body;

— convective heat exchange with air flow over the tubes;

— radiative heat exchange between the body and the LCG tubes.

Therefore, the amount of heat removed by the LCG is usually /232 determined experimetnally by measuring the difference of the liquid temperatures in the garment inlet and outlet ($\Delta t = t_{out} - t_{in}$), using the formula

$$Q = \Delta t G_w c, \qquad (7.13)$$

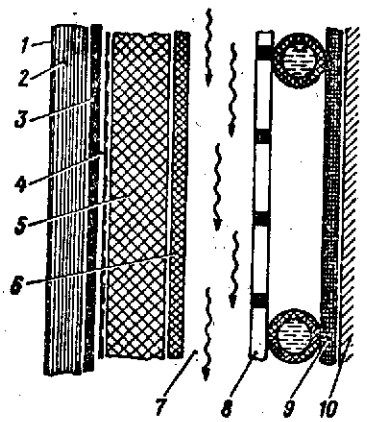

Figure 7.19. Section of pressure suit shell packet when using water cooled garment and underwear.

1 — outer garment; 2 — VBTI; 3 — anti-meteorite garment; 4 — restraint shell; 5 — primary hermetic shell; 6 — backup hermetic shell; 7 — ventilation gap; 8 — water cooled garment; 9 — underwear; 10 — man's body.

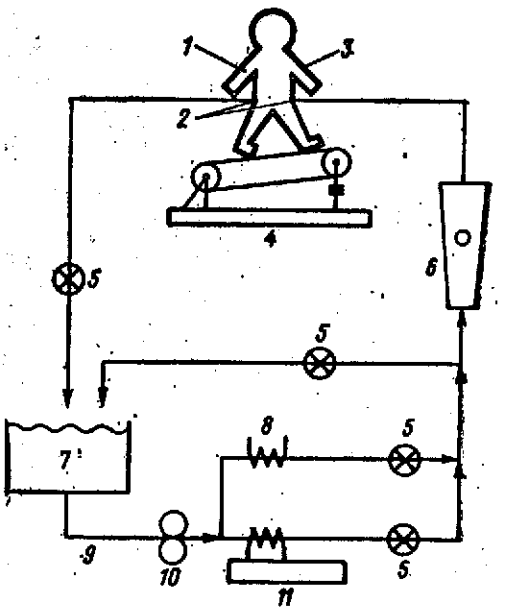

Figure 7.20. Schematic of stand for testing water cooled garment on treadmill [5].

1 — water cooled garment; 2 — temperature monitor sensors; 3 — thermal insulating garment; 4 — treadmill; 5 — valve; 6 — flow meter; 7 — water reservoir; 8 — water preheater; 9 — line; 10 — pump; 11 — heat exchanger (cooler).

where G_w is the water flowrate in kG/hr; c — the specific heat of water in kcal/(kG/°C).

In order to prevent heat dissipation into the surrounding space during these tests, a thermal protection coverall having high thermal resistance is worn over the garment being tested. Physical loading is created by having the subject perform work on a veloergometer or walk on a treadmill (Figure 7.20).

The coolant (water) supplied to the garment may be heated in the preheater 8 or cooled in the heat exchanger 11. The water is circulated by the pump 10. Water flowrate is regulated by the valve 5.

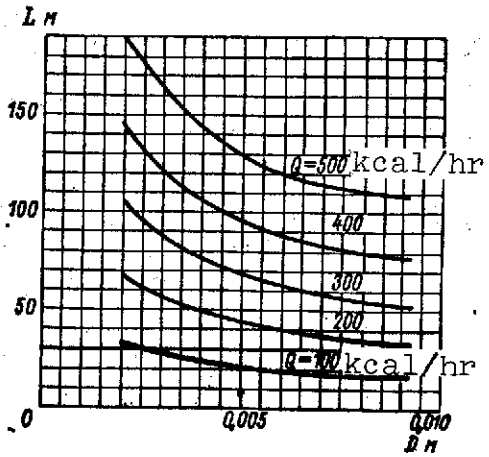

Figure 7.21. Amount of heat (Q, kcal/hr) removed by water cooled garment as function of overall length L and diameter d of tubes.

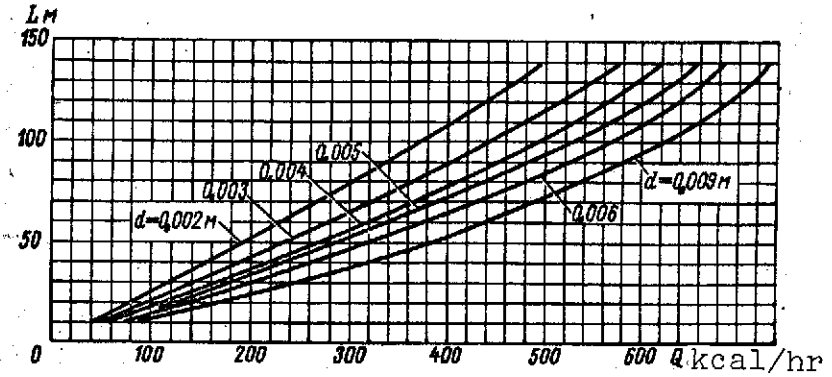

Figure 7.22. Tube length L versus amount of heat Q removed by WCG for various tube diameters d.

Many investigators have measured LCG effectiveness and determined the influence of various factors on the amount of heat removed [4, 5, 6].

Figures 7.21, 7.22, and 7.23 show the results of calculations demonstrating the variation of the amount of heat removed by the LCG as a function of tube length, tube diameter, and coolant (water) temperature.

Increase of the tube length leads to increase of the heat removal. For example, a garment with total tube length L = 50 m and tube outside diameter 4 mm, removes 245 kcal/hr, while tubes of length L = 100 m remove 500 kcal/hr.

Hydraulic calculation of the LCG is made to determine the head loss and select a construction which provides minimum hydraulic resistance to the flowing coolant. As an example, let us determine the head loss in the LCG shown in Figure 7.14 under the following conditions:

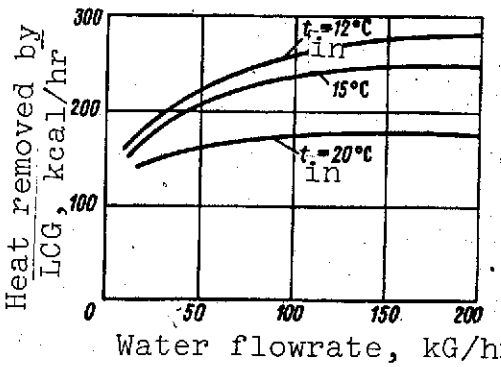

Figure 7.23. Amount of heat removed by WCG versus water flowrate for various inlet water temperatures t_{in}.

— cooling system tube length 4.5 m;

— tube diameter 3 × 4 mm; /234

— number of tubes 20;

— coolant (water) flowrate 2 liters/min;

— water temperature at garment inlet 18° C;

— water temperature at outlet 22° C;

— collector made from tubes with Ø 32 × 35.

The heat loss will be made up from:

— loss in disconnects (h_{dis});

— loss in entrance to tube 3 (h_l);

— loss in tube 3 (h_t);

— loss at outlet from tube into collector 2 (h_l).

The head loss in the disconnects (h_{dis}) for flowrate 2 liters/min is 2 × 15 = 30 mm H_2O (test results).

With water flowrate through the LCG of 120 liters/hour, the flowrate through the tube will be 0.12:20 = 0.006 m^3/hr or $1.6 \cdot 10^{-6}$ m^3/sec.

We find the liquid flow velocity through the tubes from the formula

$$v = \frac{4Q}{\pi D^2} = \frac{4 \cdot 1,67 \cdot 10^{-6}}{3,14 \cdot 9 \cdot 10^{-6}} = 0,23 \text{ m/sec}.$$

To determine the nature of the fluid flow, we find the Reynolds number using (4.1),

$$\mathrm{Re}=\frac{vD}{\nu}\ \frac{0{,}23\cdot 0{,}03}{1{,}006}\approx 690.$$

We find the kinematic viscosity for water at temperature 20° C from Table 4.8. Since Re = 556, the flow regime is laminar. In this case, the resistance coefficient for a round tube is found from (4.8)

$$\lambda_{\mathrm{lam}}=\frac{64}{\mathrm{Re}}=\frac{64}{690}=0{,}064.$$

We find the frictional head loss for liquid flow through a tube of length 4.5 m from (4.6)

$$h_f=\lambda\frac{l}{D}\ \frac{v^2}{2g}=0{,}064\cdot\frac{4{,}5}{0{,}003}\cdot\frac{0{,}23^2}{2\cdot 9{,}81}=0.25\ \mathrm{m}.$$

We find the head loss at the entrance to the tube from the manifold and at the outlet from the tube to the manifold from (4.19)

$$h'_l\xi\ \frac{v^2}{2g}=1{,}3\ \frac{0{,}236^2}{2\cdot 9{,}81}=1{,}3\ \frac{0{,}055}{19{,}62}=\ 0{,}036\ \mathrm{m}.$$

We find the loss coefficient ξ from the data shown in Figure 4.19.

The overall head loss is $\Sigma h = h_t + 2h_l + h_{dis}$ or $\Sigma h = 0{,}25 + 0.0036 + 0.0036 + 0.03 = 0.287$ m.

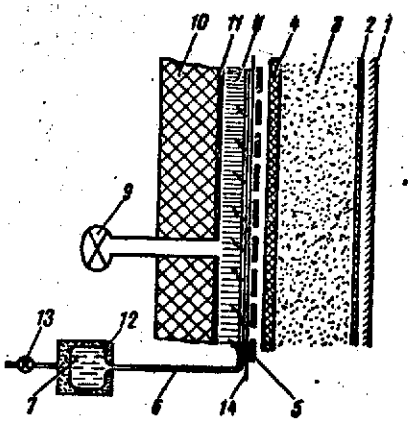

Figure 7.24. Schematic of evaporative cooling system [9].

1 — man's body; 2 — underwear; 3 — ventilation gap; 4 — pressure suit hermetic shell; 5 — pressure suit restraint shell; 6 — water inlet tub;e 7 — water tank; 8 — water absorbing layer (wick); 9 — vacuum valve; 10 — pressure suit thermal protective layer; 11 — hermetic shell; 12 — rubber vessel (membrane); 13 — air inlet valve; 14 — protective shell.

Evaporative Cooling System

A schematic of an evaporative cooling system is shown in Figure 7.24. Two hermetic shells 11 and 14, between which there is a layer 8 of porous material capable of absorbing moisture, are worn over the pressure suit. The coolant coming from the tank 7 is absorbed by the wick 8. When the vacuum valve 9 is opened, the pressure falls in the space between shells 11 and 14 and this causes violent boiling of the liquid in the wick.

The heat required for the vaporization process (about 570 kcal/kG water) comes from the pressure suit. /235

The layer 8 which absorbs the moisture can be made from several layers of knit cotton cloth [9].

The operation of the evaporative cooling system can be automated by connecting the valve 9 to a temperature sensor located on the wearer's skin.

5. Design of Pressure Suit for Lunar Explorer

In the development of the pressure suit for lunar exploration, approaches have been noted involving modification and further development of the soft pressure suit design and the

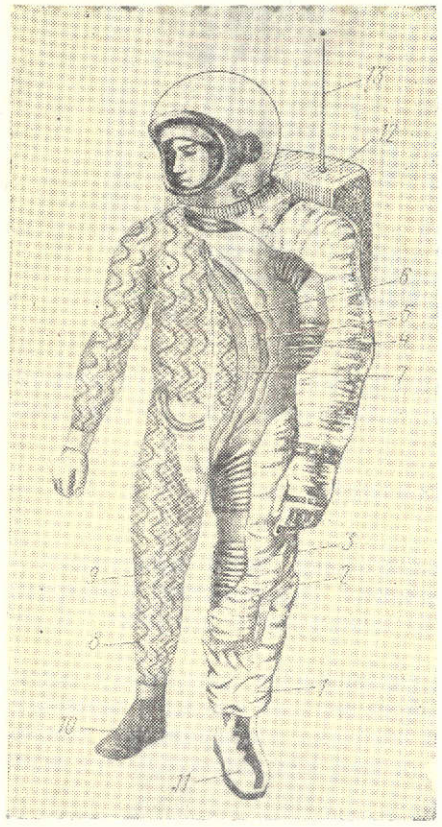

Figure 7.25. Possible variant of soft pressure suit for astronaut egress to the lunar surface [1].

1 — outer garment; 2 — VBTI; 3 — protective shell; 4 — restraing shell; 5 — hermetic shell; 6 — backup hermetic shell; 7 — liner; 8 — ventilating system tubes; 9 — liquid cooling garment; 10 — socks; 11 — boots; 12 — life support system pack; 13 — antenna.

creation of new designs of hard and semi-hard pressure suits.

The first approach involves improving the soft pressure suit to increase the protective properties of the outer garment, VBTI thermal resistance, mobility of man in the pressure suit, improvement of anti-meteoroid protection, improvement of helmet optical characteristics, and also the development of lunar footwear.

Figure 7.25 shows a possible variant of the soft pressure suit for lunar surface exploration, which includes an outer garment, anti-meteoroid garment, VBTI, protective shell, restraing shell, hermetic shell (one or two), liner (to facilitate donning), ventilating system, helmet, LCG, thermal socks and boots. The knees and elbows have additional protection in the form of netting made from fine metal fibers (Figure 7.26).

The outer garment of the American A7L pressure suit is made of glass cloth (Figure 7.27). Very fine glass fiber 3 — 5 microns thick (beta fiber) is used to make the glass cloth.

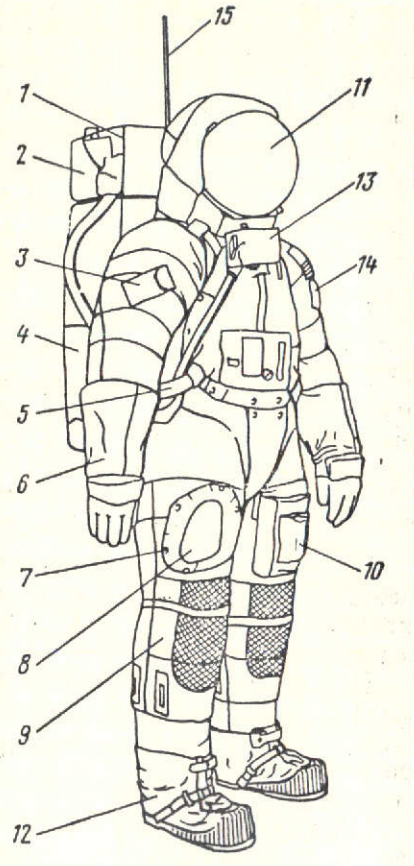

Figure 7.26. Outer garment of American A7L pressure suit (Flight, 10 July, 1969).

1 — emergency oxygen supply system; 2 — radio; 3 — protective glasses pocket; 4 — autonomous life support system; 5 — hose for oxygen flow from emergency system; 6 — removable protective gloves; 7 — radiation sensor; 8 — urine collector fitting; 9 — protective netting made of metal threads; 10 — tool pocket; 11 — light filter; 12 — lunar boots; 13 — backpack system remote control; 14 — flashlight pocket; 15 — antenna.

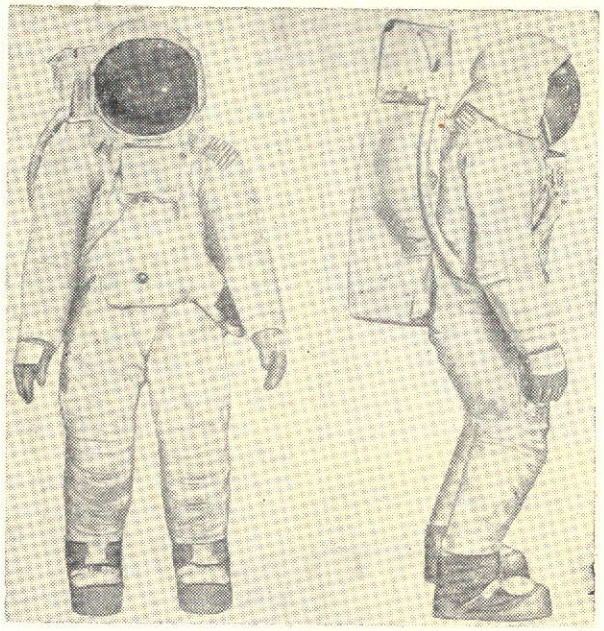

Figure 7.27. General view of American A7L suit (Aviation Week and Space Technology, March 3, 1969).

Increase of the VBTI resistance is explained by the presence of considerable thermal flux from the heated lunar surface and also by the increase of the amount of heat received by the pressure suit as a result of change of the outer garment optical characteristics, as lunar dust settles on this garment.

Increase of anti-meteoroid protection is associated with the presence of secondary meteoric bodies (fragments) which have

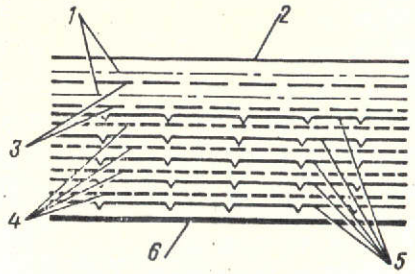

Figure 7.28. Section of outer garment packet of American A7L pressure suit (typical packet).

1 — aluminized polyamide film (2 layers); 2 — glass cloth; 3 — glass cloth netting (2 layers); 4 — dacron voile; 5 — mylar film (5 layers); 6 — nylon anti-meteorite layer with neoprene coating.

Figure 7.29. American A4-H soft pressure suit.

comparatively low velocity (1 — 1.5 m/sec) but considerable damaging force.

Figure 7.28 shows the arrangement of the anti-meteoroid protection of the A7L pressure suit, consisting of nylon fabric coated with neoprene rubber. Testing of the anti-meteoroid protection was conducted using small spheres of silicate glass /236 of diameter 0.25 — 0.4 mm with velocity 7.2 km/sec at the instant of impact.*

Increase of pressure suit mobility is associated with the necessity for movement over the lunar surface and also the performance of the planned scope of operations (drilling, specimen collection, and so on). Increase of pressure suit mobility is

*Aviation Week and Space Technology, Vol. 90, No. 9, 1969.

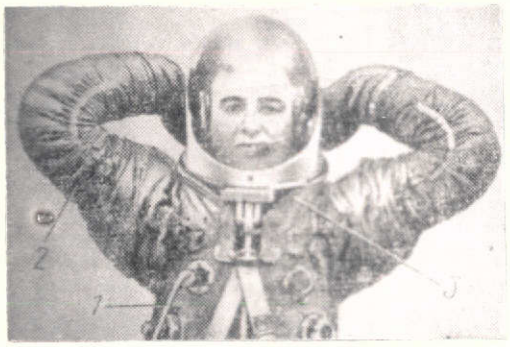

Figure 7.30. American A7L pressure suit (Aviation Week, Vol. 90, No. 1, January 6, 1969).

1 — communications connector; 2 — hermetic elbow bearing; 3 — protective garment attachment lacing.

achieved by installing "accordion" type hinges, as was done in the A4-H pressure suit (Figure 7.29), or installing hermetic elbow bearings (Figure 7.30).

Improvement of the helmet optical properties is associated with the necessity for performing operations under different illumination (under lunar daytime and nighttime conditions).

The helmet of the American A7L pressure suit does not have a pivoting visor. The transparent part of the helmet is made of polycarbonate. A port for taking liquid food and water is provided in the front part of the helmet (Figure 7.31). /238

The removable portion of the helmet 6 with protective visor 2 (anti-meteoroid protection) is placed over the helmet prior to egress onto the lunar surface. Two light filters are provided for working in open space and on the lunar surface. The inner light filter blocks no more than 30% of the light energy in the visible part of the spectrum. The outer light filter is used in case of direct solar illumination and transmits only 16% of the visible light. A gold coating is applied to the light filter by metal vapor deposition in a hard vacuum.*

The pressure suit footwear must have good thermal protective properties and protect the soles of the feet against overheating when walking over the hot lunar surface (Figure 7.32).

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*Abstract Journal, Raketostroyeniye, No. 2, 2.41.256, 1970.

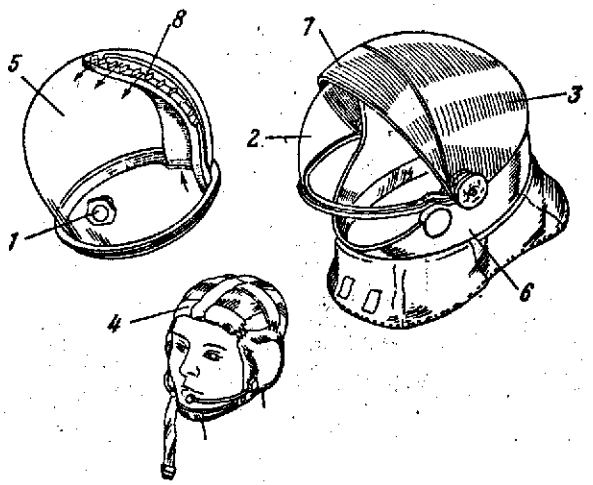


Figure 7.31. Helmet of American A7L pressure suit (Flight, 10 July, 1969).
1 — liquid food intake port; 2 — protective visor; 3 — outer light filter; 4 — communications helmet; 5 — polycarbonate shell; 6 — removable part of helmet; 7 — inner light filter; 8 — ventilator.

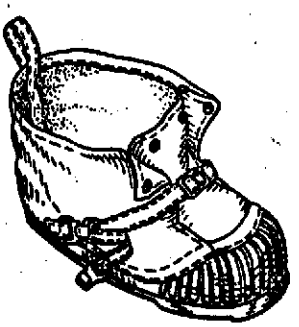


Figure 7.32. Removable lunar boot.

At the same time, the footwear must be strong, light, and thermally stable in the temperature range from +150 to -200° C. Footwear made in the form of removable boots of temperature resistant fabric can meet these requirements. In these boots, silicone rubber or leather is used for the sole. The use of a wooden sole of the Dutch shoe type is also possible.

The second approach to the development of the pressure suit for the lunar explorer is, as mentioned before, the hard pressure suit.

The advantages of the hard suit include the possibility of creating a high differential pressure (up to 1 kG/cm^2) and comparatively high fire safety. However, the hard suit also has drawbacks such as high weight, greater restriction of wearer mobility than in the soft suits, and in the absence of differential pressure, difficulty in selecting a comfortable seat in the spacecraft. /239

Figure 7.33. American AX-1 hard pressure suit [8].

1 — waist hinge in "accordian" form; 2 — soft hinges providing sideward movement of legs; 3 — hermetic bearings.

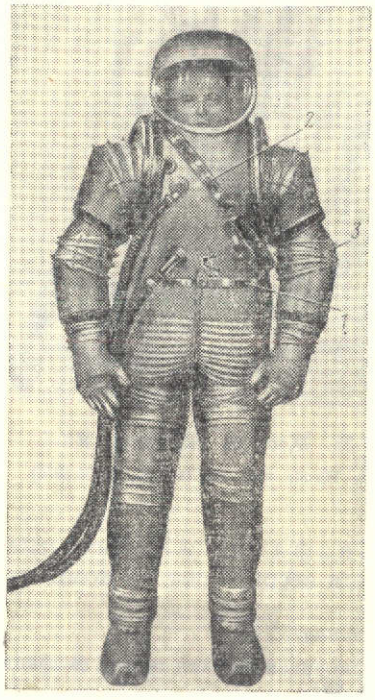


Figure 7.34. American RX-1A pressure suit.

1 — waist joint; 2 — shoulder joint; 3 — tension cable which takes axial loads.

It has been suggested that hard pressure suits will find application as the protective outfit for lunar explorers in the very near future. However, a final evaluation of their advantages and disadvantages can be made only on the basis of test results.

Figure 7.33 shows the AX-1 hard pressure suit developed by the Ames Research Center [8]. The suit weighs 32.8 kG. It is made basically from glass cloth impregnated with epoxy resin. A characteristic of this suit is the presence of a large number of hermetic bearings (more than 20).

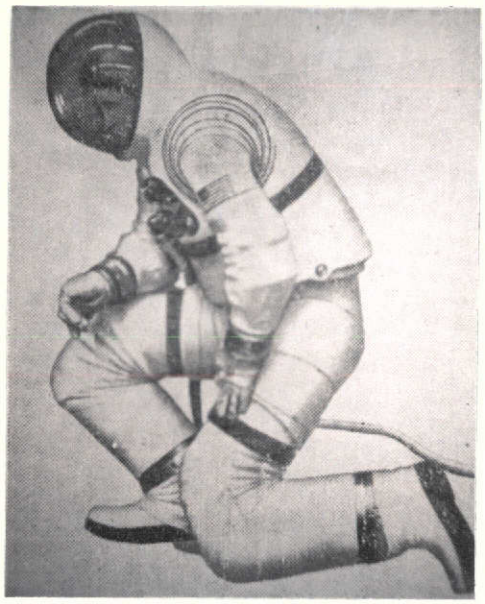


Figure 7.35. RX-5 hard suit (Aviation Week, Vol. 90, No. 15, April 14, 1970).

The RX-1A hard pressure suit shown in Figure 7.34 is made by the Litton firm. The suit shell consists of two halves with a disconnect at the waist. There is also another disconnect running across the right shoulder.

The suit is equipped with six hermetic bearings (two shoulder, two elbow, and two wrist). Raising of the arm in the shoulder joint, bending of the arm in the elbow joint, and bending of the leg in the knee joint are accomplished with the aid of hinges. Axial loads are taken by the cables 3.

The ankle universal joint provides foot rotation in all directions. Bending of the wrist is also accomplished with the aid of a universal joint. The hip hinge is soft. It is possible that this hinge is made of rubberized fabric. The axial forces /240 are taken by cables located in guides. The suit is equipped with a bubble helmet, the visor is fixed. The boots are made in the form of Dutch shoes with wooden soles.

Another modification of the hard suit, designated RX-5, is shown in Figure 7.35.

There are also semi-hard suit designs in which the torso is made of metal and the sleeves and pants are made of fabric.

The hard torso of the suit is made from aluminum alloys or polymer materials (glass reinforced plastics).

6. Apollo Program Lunar Explorer Pressure Suit

In order to have more complete information on the possible characteristics of the soft pressure suit, we shall present additional data on the American A7L pressure suit with autonomous life support system.

The A7L pressure suit was constructed by International Latex (see Figures 7.26 and 7.27). A brief weight breakdown of the pressure suit system is given in Tables 7.3 and 7.4.

The ventilation system of the A7L pressure suit has a device for connecting to the onboard and portable life support systems (Figure 7.36). /241

The oxygen entering the pressure suit at the fitting 1 flows through a hose to the helmet where it is used for breathing. The gas flow from the helmet is directed to the arms and legs, where it is gathered and dumped overboard through the fitting 2.

Tests of the pressure suit operational characteristics made at the MSC in Houston gave the following results:

— suit donning time no more than 5 minutes;

— glove donning time 21 — 58 seconds;

— regulation of tie-down system about 1 minute;

— connecting oxygen supply hose 6 seconds;

— connecting water supply hose 8 seconds.

TABLE 7.3

APPROXIMATE WEIGHT BREAKDOWN OF A7L PRESSURE SUIT

Elements	Weight, kG	
	Element	Total
Suit shell		14.6
protective shell	1.2	
restraint shell	6.5	
hermetic shell	3.5	
liner	0.6	
ventilation system	1.5	
gloves	0.3	
communication plug	1.0	
Helmet		2.2
Interchangeable light filters		2.0
Other details		1.0
	Total	19.8 kG

TABLE 7.4

APPROXIMATE WEIGHT BREAKDOWN OF A7L PRESSURE SUIT SYSTEM

Elements	Weight, kG	
	Element	Total
Suit		19.8
Outer garment		4.5
glass cloth shell	2.0	
film (7 layers)	0.5	
anti-meteorite layer	2.0	
Lunar gloves		1.2
Lunar boots		2.2
Liquid cooled garment		2.0
Communication helmet		0.4
Other details		1.2
	Total	31.3 kG

The following results were obtained in treadmill tests:

a. without differential pressure and at walking speed 1.3 km/hr, the energy expenditures were 234 kcal/hr, while at a speed of 4 km/hr, the energy expenditures were 443 kcal/hr.

b. with differential pressure and walking speed of 2.4 km/hr, energy energy expenditure was 530 kcal/hr.

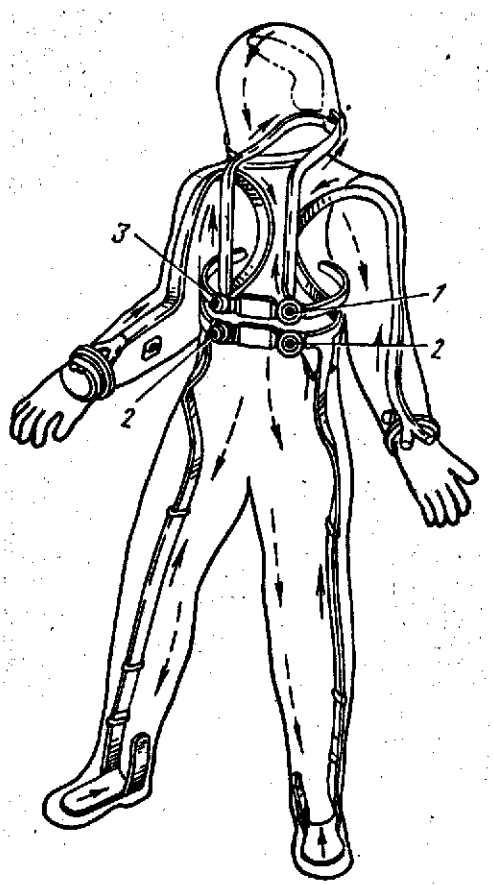


Figure 7.36. Ventilation system of the A7L pressure suit (Flight, 10 July, 1969).
1 — oxygen inlet fitting;
2 — oxygen outlet fitting;
3 — emergency oxygen supply fitting.

The autonomous life support system (ALSS) manufactured by Hamilton Standard* permits the astronaut to perform the planned work program on the lunar surface over a period of four hours. In case of emergency, there is a reserve unit designed to supply oxygen for 30 minutes. The overall system weight is 54 kG, of which 18 kG is the weight of the emergency oxygen supply system (Table 7.5).

The system provides:

— oxygen supply at a pressure of about 200 mm Hg;

— absorption of CO_2;

— water supply to the LCG;

— radio communication between crewmembers and with the spacecraft.

*Space World, July, 1969, Vol. F-7-67, No. 7.

TABLE 7.5

APPROXIMATE WEIGHT BREAKDOWN OF AUTONOMOUS LIFE SUPPORT SYSTEM

Components	Weight, kG		Components	Weight, kG	
	Comp.	Total		Comp.	Total
O_2 supply system		4.8	fittings	1	
O_2 bottle (70 kG/cm^2)	1.8		wiring	0.9	
fittings	2		Communications:		4.2
lines	1		radio set	2.2	
Regeneration system		4.5	fittings	1.2	
absorption canister	1.7		wiring	0.8	
fan	0.8		Remote controls		1.5
fittings	1		Pack housing		2.5
hose and disconnects	1		Emergency O_2 system		18
Cooling system		5.7	O_2 bottle		
sublimation cooler	2		fittings		
H_2O tank	0.8		lines		
fittings	1.1		Consumables:		7
lines	0.8		O_2 in bottle	0.5	
LCG water supply system		2.3	cooling H_2O	3.8	
H_2O pump	0.5		water in LCG system	0.9	
fittings	1		emergency O_2 supply	2.6	
lines	0.8				
Electrical equipment		3.5			
battery	3			Total	54.4 kG

The water supply system contains about six liters of water at a pressure of 1.4 kG/cm^2. A reservoir is provided to store an additional 113 grams of liquid coming from the regeneration system.

The ALSS consists of six basic subsystems: oxygen supply, /242 regeneration, cooling, water supply to LCG, electrical equipment, and communications.

The pack dimensions are: height 650 mm, width 445 mm, and thickness 262 mm.

The 16.8 V silver zinc battery drives the oxygen feed blower, LCG water pump, and radiotelemetry equipment. The pack housing is made of glass reinforced plastic.

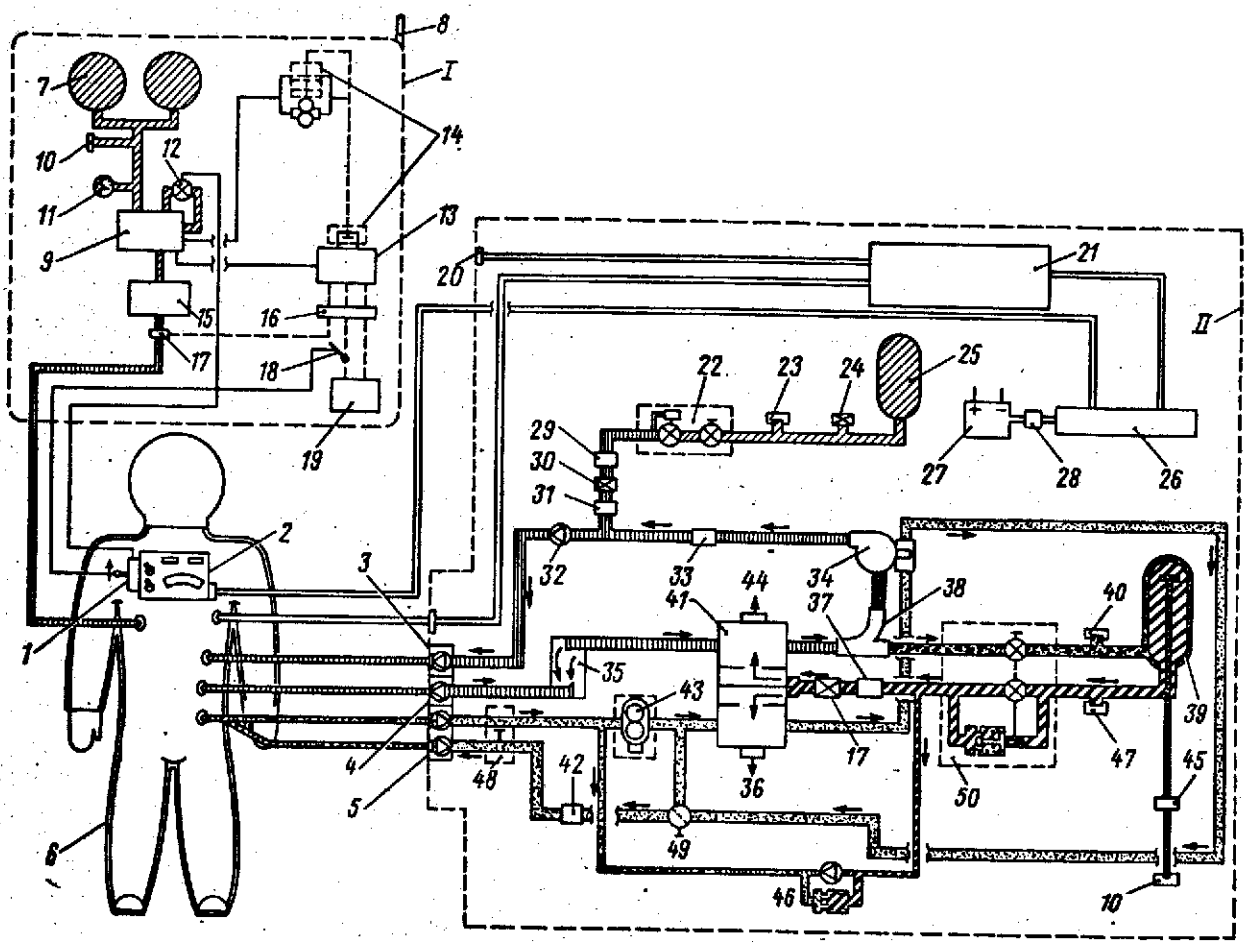
We mentioned previously that the emergency oxygen supply system weighs 18 kG and contains 1.81 kG of oxygen. This system is designed to operate for 30 minutes, the oxygen is stored at 471 kG/cm^2 pressure.

The sublimative cooler is equipped with a porous nickel plate.

Regulation of the temperature of the water supplied to the LCG is accomplished by means of a bypass line in the following limits: 7 — 10, 15 — 18, 23 — 26° C (Figure 7.37).

The regeneration canister absorber consists of lithium hydroxide (LiOH).

The oxygen supply system provides O_2 circulation at a rate of 40 liters(s)/min. The oxygen supply is stored in a bottle at 70 kG/cm^2 pressure. The bottle contains about 460 grams of O_2. The bottle length is 430 mm, diameter 150 mm. The bottle /244
can be recharged aboard the spacecraft for reuse. An audio signal is actuated when the oxygen supply falls below a specified level.



- High pressure O_2
- O_2 circulation in suit sys.
- Condensate (O_2 and moisture) collection
- Water flow to WCG
- Water (coolant) flow to heat exchanger
- Electric line
- Manual valve
- Pressure regulator
- Pressure sensor
- Temperature sensor
- Flowmeter
- Bypass valve
- Disconnect
- Disconnect with check valve

Figure 7.37. Schematic of ALSS.

I — emergency oxygen supply system; II — backpack life support system; 1 — oxygen flood system actuator; 2 — remote control unit; 3 — oxygen connector; 4 — oxygen connector; 5 — connector for water supply to liquid cooled garment; 6 — pressure suit; 7 — emergency oxygen system bottles; 8 — antenna; 9 — heater; 10 — filler; 11 — high-pressure pressure gage; 12 — shutoff valve; 13 — heater system; 14 — oxygen heating control;

Continuation of Figure 7.37:

15 — regulator; 16 — terminal block; 17 — temperature sensor; 18 — supply on-off switch; 19 — battery; 20 — antenna lead; 21 — pressure suit communications system; 22 — pressure regulator; 23 — charging connector; 24 — main oxygen supply pressure sensor; 25 — oxygen bottle; 26 — terminal box; 27 — battery; 28 — electric power consumption sensor; 29 — oxygen flow sensor; 30 — suit pressure sensor; 31 — low suit pressure warning; 32 — check valve; 33 — ventilation flow sensor; 34 — blower; 35 — absorber canister; 36 — dicharge to vacuum; 37 — flow limiter; 38 — water separator, 39 — water reservoir; 40 — water drain; 41 — sublimative heat exchanger; 42 — liquid cooled garment temperature sensor; 43 — pump; 44 — discharge to vacuum; 45 — drinking water pressure sensor; 46 — water supply shutoff and bypass valve; 47 — connector for filling water reservoir; 48 — LCG inlet temperature sensor; 49 — bypass valve; 50 — bypass and control valves.

REFERENCES

1. Umanskiy, S. P. Snaryazheniye letchika i kosmonavta (Equipment for the Pilot and Cosmonaut), Voyenizdat, Moscow, 1967.

2. Grishakov, I. G. and S. P. Umanskiy. "Equipment for the Pilot and Cosmonaut," Aviatsiya i kosmonavtika, No. 7, 1965.

3. Roth, E. M. Bioenergetics of Space Suits for Lunar Exploration. NASA SP-84.

4. Burton, D. R. Engineering View of Personal Thermal Conditioning, World Aerospace Systems, Vol. 1, No. 10, 1965.

5. Jenning, D. C. Water Cooled Space Suit. Journal of Spacecraft and Rockets, Vol. 3, No. 8, 1966.

6. Burton, D. R. Performance of Water Conditioned Suits. Aerospace Medicine, Vol. 37, No. 5, 1966.

7. Heater, M. D. NASA Considering Litton-Developed Hard-Shell Suit for Explorations. Missiles and Rockets, Vol. VIII, No. 24, 1964.

8. Vykukal, H. C. Advanced Developments in Hard Pressure Suit Technology. Konstruirovaniye i tekhnologi mashinostroyeniye, No. 4, 1968.

9. Votta, F. and L. A. Spano. Experimental Study of a Passive Thermal Control System for Space Suits. Aerospace Medicine, Vol. 40, No. 4, 1969.

CHAPTER 8
MATERIALS AND FABRICS IN PRESSURE SUIT CONSTRUCTION

The development of pressure suit construction has led to /245
the need for finding and developing new materials to improve pressure suit construction quality, improve reliability, and increase suit service life.

The development of such materials is complicated by the necessity for taking into account the possible physical and mechanical changes of the materials under the influence of space factors (deep vacuum, radiation, large temperature differential). It is well known that, in a large group of polymers, the influence of these factors leads to the onset of molecular breakdown processes — destruction. For example, fluorlon loses its strength nearly completely under 500-hour irradiation by electrons, while kaptron and lavsan change their strength characteristics very little under the same conditions. Destruction of the polymers is usually accompanied by the formation and release into the surrounding space of gaseous products, many of which are toxic. The structuring process, the reverse of destruction, takes place in the polymers under the influence of various factors. In this case, the polymer may not only not reduce its initial strength but, conversely, may increase its strength markedly.

We shall examine the properties and characteristics of the materials used in pressure suit construction.

1. Textile Materials

Textile materials are used in pressure suit construction primarily for fabrication of the shells, outer garment, and thermal protection garment.

The most important such materials are fabrics, tapes, and threads.

Fabrics

General information and fiber classification. Fabric is formed from two mutually perpendicular systems of threads which are interwoven with one another — the warp threads running along the fabric and the woof threads running across the fabric.

Fabric threads are prepared by twisting (spinning) fibers (yarns) of various origin.

The strength of threads is considerably less than the strength of the fibers composing them, since breaking of the threads takes place as a result of a tensile force overcoming the bonding forces between the thread fibers, which may be less than the strength of the fibers themselves.

In turn, the strength of fabrics made from threads may be considerably lower than the strength of the threads themselves because of increase of the stresses acting in the threads at /246
locations of sharp thread bends in the fabric weaves.

The properties of fibers depend to a considerable degree on their geometric dimensions.

It is customary to express the average thickness of textile fibers in microns, metric number, denier units, or in tex units.

Fiber metric number is determined from the formula

$$N=\frac{l}{G}, \tag{8.1}$$

where l is the fiber length in meters; G — fiber weight in grams.

In other words, we can say that the fabric (thread) number indicates the number of meters of the thread which weigh one gram.

The relationship between fiber diameter in microns and metric number is defined by the expression

$$d=\sqrt[4]{\frac{4\cdot 10^6}{\pi\gamma N}}, \tag{8.2}$$

where d is the fiber diameter in microns; N — the fiber metric number; γ — the fiber specific weight in g/cm^3.

The relationship between the fiber metric number and denier is defined by the relation

$$D=\frac{7000}{N}. \tag{8.3}$$

The relationship between metric number and fiber thickness in tex is defined by the relation [1]

$$T=\frac{1000}{N} \quad \text{tex}. \tag{8.4}$$

Tex denotes the thickness of a fiber (thread) one kilometer of which weighs one gram.

In resistance of materials strength (breaking stress) is expressed in terms of the ultimate strength $\sigma_{ult} = P/S$, where P is the actual (breaking) force in kG; S — the cross section area in mm^2.

The difficulty in exact determination (measurement) of thread (fiber) cross section dimensions led to the adoption of an arbitrary unit for evaluating thread strength — *the breaking length*, i.e., the thread length at which it breaks under the influence of its own weight. The breaking length of viscose fiber is 13 — 22 km. The strongest fibers produced industrially have a breaking length of 60 — 80 km [2].

On the basis of origin, the fabric fibers are divided into *natural*, *artificial*, and *synthetic*.

The natural fibers include cotton, wool, linen, silk, and asbestos.

Cotton fiber consists basically of cellulose. Its strength characteristics are shown in Table 8.1.

The strength of cotton fiber increases when it is moistened. Cotton fabrics are used in pressure suits for fabricating various shells and knit underwear.

In accordance with Government Standard GOST 3279-63, cotton fibers are divided on the basis of strength into seven grades. The thickness of medium fiber cotton corresponds to numbers from 4500 to 6000 (0.17 — 0.22 tex).

TABLE 8.1*

PHYSICO-MECHANICAL CHARACTERISTICS OF SOME TEXTILE FIBERS [3]

Fiber	Sp.wt. g/cm³	Breaking strength, kG/mm²	Breaking length km		Elongation at break %		Resistance to abrasion by some fiber in relative units
			Dry	Wet	Dry	Wet	
Wool	1,28—1,33	15—25	23,0—28	27—30	25—40	30—60	430
Cotton	1,52	23—45	8,5—13	7—12	7—10	9—12	50
Linen	—	60—95	—	—	2—3	20—25	—
Viscose	1,52	16—78	13,0—22	7—11	15—30	25—35	79
Acetate	1,32	16—60	10,0—13,5	7—9	17—30	28—35	50
Triacetate	1,28	—	10,5—11	6—7	25	28—30	—
Kapron (polyamide)	1,14	35—72	31,5—46	27—40	20—80	25—90	640
Lavsan (polyester)	1,38	50—80	32,0—40	31—40	20—60	20—60	290
Nitron (polyacrylnitrile)	1,17	20—40	23,0—30	21—28	16—30	16—30	53
Chlorene (chlorinated polyvinyl chloride base)	1,50	18—40	18,0—25	18—25	20—40	20—40	34

*Commas in the numbers indicate decimal points.

Wool fiber consists basically of keratin (protein substance). High quality wool has fiber length up to 50 —200 mm. The wool fiber thickness falls in the range from 7 to 240 microns. Valuable properties of wool are its high hygroscopicity and comparatively high thermal resistance. Wool is used to make thermal protective clothing, underwear, and socks.

Bast fiber (linen) consists basically (to 80%) of cellulose. The fiber strength reaches 95 kG/mm², its elongation is only 2 — 3%. Linen fiber has high hygroscopicity and its strength and elongation increase in the wet condition. The average fiber diameter is 12 — 17 microns. /247

Linen fabrics are used in fabricating underwear materials and strong tapes.

Among the artificial fibers, glass fiber has been used most widely in pressure suit construction. The viscose and acetate fibers are used as additives to cotton in fabricating underwear.

Glass fiber is obtained from molten glass. Fibers of thickness from 3 to 100 microns are used in the textile industry. Depending on the basic material, the operating temperature limits for glass fabrics are 600 — 1000° C. In comparison with the other fibers, glass fiber has the highest strength (180 to 400 kG/mm^2) with the smallest section diameter.

Viscose fiber is obtained by chemical treatment of wood cellulose. It has high water absorption. The drawbacks of this fiber are low resistance to abrasion and low thermal stability.

Acetate fiber is obtained by treating cotton or wood cellulose with acetic acid. This fiber is soft but has low strength and resistance to abrasion.

The synthetic fibers are made from polyethylene, polypropylene, polyamide, polyester, and other high-molecular compounds.

Polyethylene fibers are made from high, medium, and low pressure polyethylene. Outside the Soviet Union, they are termed kurlene, marlex, and so on.

The basic physical and mechanical properties of polyethylene /248 are shown in Figure 8.1.

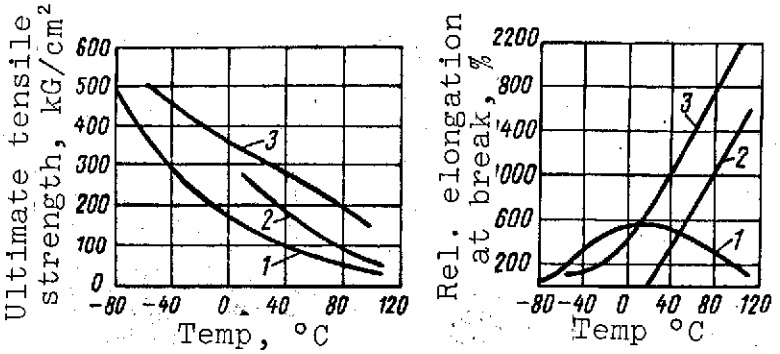


Figure 8.1. Ultimate strength and relative elongation of polyethylene versus temperature [4].

1 — HP polyethylene; 2 — LP polyethylene with molecular weight 30,000; 3 — LP polyethylene with molecular weight 350,000.

High pressure (HP) polyethylene is resistant to aggressive media, under certain conditions it is resistant to the action of alcohols, soaps, and fatty oils, bonds easily and strongly.

Low pressure (LP) polyethylene is a harder material and has higher thermal stability than HP polyethylene (see Figure 8.1).

A drawback of the polyethylene materials is their aging (change of physico-mechanical properties) under the action of solar radiation and atmospheric oxygen.

The polypropylene fibers differ very little from polyethylene fibers in their chemical properties. The moisture and gas impermeability and the mechanical properties of polypropylene are far higher than for polyethylene, while the specific weight is lower. The drawbacks of polypropylene include the poor cold resistance of certain grades and aging under the influence of solar rays.

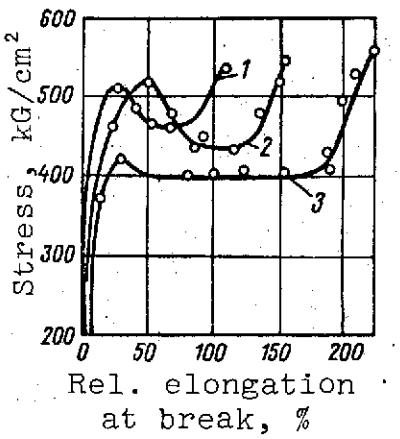


Figure 8.2. Polyamide tension diagram.

1 — P-38; 2 — P-AK-7; 3 — kapron [4].

Polyamide fibers. The most widely used polyamide fiber is kapron (nylon in the USA, perlon in East and West Germany, silon in Czechoslovakia, and enkalon in Holland). The coefficient of thermal expansion of the polyamides is approximately ten times that of the metals. Their melting point is 180 — 220° C.

The polyamides can be pressure cast, are easily drilled, turned, and milled.

Figure 8.2 shows a polyamide tension diagram and Figure 8.3 shows the variation of polyamide bending strength as a function of temperature.

The polyamide fibers are used to make fabrics for pressure suit shells and strong tapes.

In the USSR, *polyester fibers* are called lavsan (dacron in the USA, terilene in England, and lanon in East Germany).

Although polyester fiber is somewhat inferior to polyamide fiber in strength, it has high elasticity, light resistance, and high thermal stability.

Dupont (USA) produces polyester fiber (dacron) and reports /249 that it has strength from 36 to 62.1 breaking kilometers with breaking elongation of 40 and 11%, respectively [2].

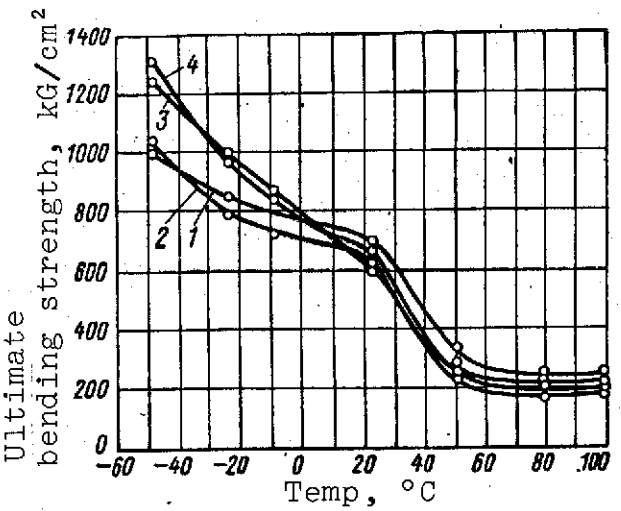


Figure 8.3. Ultimate bending strength of polyamides versus temperature [4].

1 — P-68; 2 — kapron; 3 — P-6; 4 — P-AK-7.

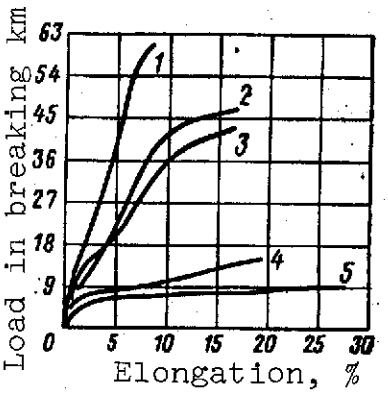


Figure 8.4. Strength characteristics of some fibers [2].

1 — high-strength terilene; 2 — nylon; 3 — medium-strength terilene; 4 — viscose silk; 5 — acetate silk.

The specific weight of polyester fiber is about 1.4 g/cm^3.

The characteristics of some polyester fibers are shown in Figure 8.4.

Thanks to their comparatively high thermal stability, the polyester fibers are used in making the astronaut's outer clothing and pressure suit shells. Some data characterizing the thermal stability of the various fibers are presented in Table 8.2.

Phenylon is an aromatic polyamide. Characteristic of /250
phenylon, just as the other aromatic polyamides, is a high melting point 430° C [5], and consequently, high thermal stability (to 260° C) and good radiational and chemical stability. Following are the basic physico-mechanical properties of the phenylon plastics:

TABLE 8.2

FIBER THERMAL STABILITY CHARACTERISTICS [3]

Fiber	Temperature, °C, at which occurs			
	Decomposition	Strength loss	Softening	Melting
Cotton	150	120	—	—
Flax	—	120	—	—
Wool	130—135	—	—	—
Silk	150—170	—	—	—
Viscose	180—200	120—130	—	—
Copper-ammonium	150	120	—	—
Acetate	90—105	95—105	200	230
Protein (Zein)	—	177	—	243—246
Polyethylene	—	—	—	110—120
Polypropylene	—	100	140	160—165
Polyvinyl chloride	—	65—75	65—75	—
Perchlorvinyl (chlorene)	—	70—80	95—100	—
Polyvinylidene chloride	—	100	140—160	—
Polyamide	—	90—100	170—235	215—255
Polyester	—	160—170	230—240	250—255
Polyacrylonitrile	—	180—200	235	—
Glass	—	315—350	500—815	1200—1600
Asbestos	—	200—400	—	1450—1550

Specific weight	1.33 — 1.36 g/cm^3
Tensile ultimate	800 — 1200 kG/cm^2
Charpy impact strength	15 — 35 kG/cm/cm^2

Phenylon VA (TU V-119-68) is used to obtain fiber with operating temperature 200 — 250° C and brittle temperature down to -70° C [5].

In pressure suit construction, phenylon is used to make the outer garment and as a sealing material operating in the temperature range from -70 to +250° C.

Fabric strength testing. Fabric materials are anisotropic and do not obey Hooke's law and the principle of independence of force action, therefore the deformation of a fabric in any particular direction depends on the relationship between the

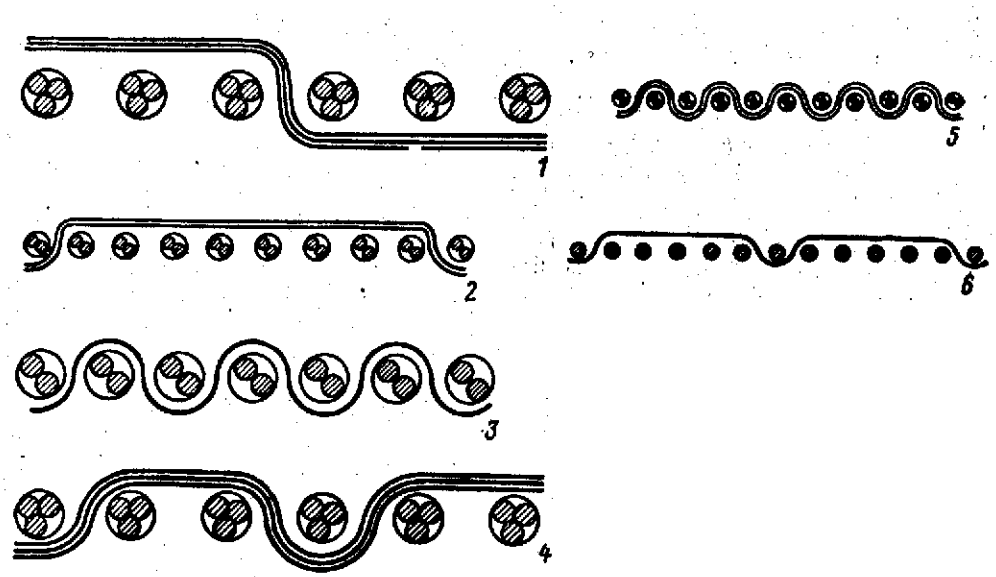


Figure 8.5. Possible thread weaves in fabrics.
1 — serge 3/3; 2 — atlas 8/2; 3 — canvas; 4 — serge 1/2; 5 — canvas; 6 — atlas 5/3.

loads acting in the warp and woof directions.

Depending on the nature of the weave, the warp and woof threads form cells of one form or another (Figure 8.5). In pressure suit shells made from fabric, we must consider the weakening of the fabric due to the fact that, under the action of the applied load, the stretched threads increase the twist of the unloaded threads causing additional stresses in the latter.

Assortment of fabrics. A broad assortment of fabrics is used in pressure suit construction. The requirements imposed on the fabrics depend on their application. For example, fabric for the restraint shell must have the required strength and small elongation, must resist abrasion and tearing well. The physical and mechanical properties of some fabrics are given in Table 8.3, and the loading scheme for tear testing is shown in Figure 8.6 (GOST 3813-47).

TABLE 8.3

PHYSICAL AND MECHANICAL PROPERTIES OF SOME FABRICS

Fiber	Weight g/m^2	Breaking load for 50×200 strip kG		Elongation %		Tear resistance kG
		Warp	Woof	Warp	Woof	
Lavson	300	280	200	13	—	10
Kapron	400	480	400	25	—	20
Kapron	300	400	280	25	—	30
Kapron	140	155	100	25	—	5
Kapron	250	410	145	30	25	10
Kapron	45	40	32	20	—	—
Phenylon	200	140	135	15	—	10

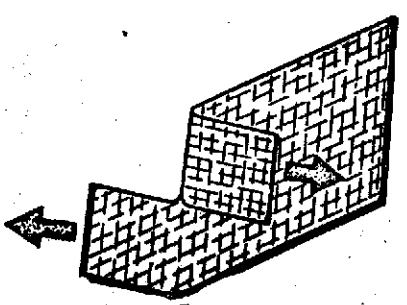


Figure 8.6. Fabric tear testing scheme.

While fabric tensile strength depends primarily on thread strength, fabric resistance to tearing depends mainly on fabric structure. For example, the serge weave synthetic fabrics have higher tear resistance than fabrics of other structures (Figure 8.7). If the pressure suit restraint /251 shell is at the same time the pressure retaining shell, it is made from rubberized fabric.

Depending on the imposed requirements, the hermetic shell may be made fron single-layer, two-layer, or three-layer rubberized fabric (Figure 8.8). In the two-layer fabric, the rubber sealing layer (thickness to 0.5 mm) is located between the fabric layers, in the three-layer construction the middle layer is rubberized on both sides.

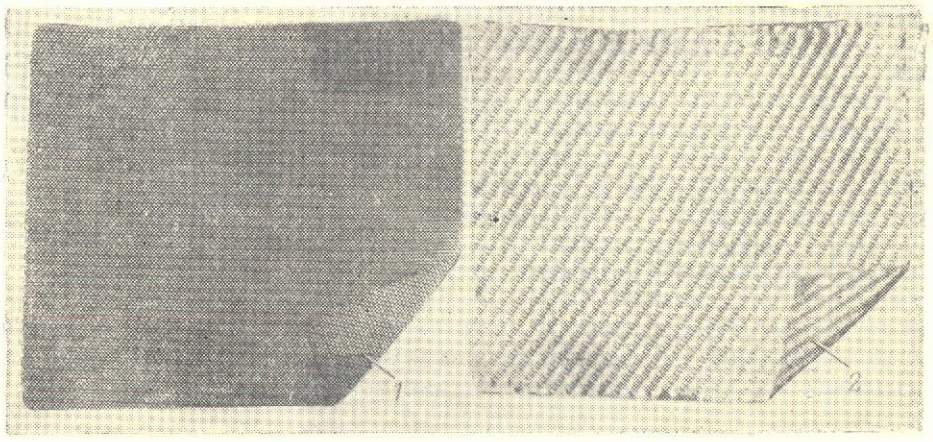


Figure 8.7. Fabrics made from synthetic fibers.
1 — fabric made from canvas-weave kapron; 2 — fabric made from serge-weave kapron.

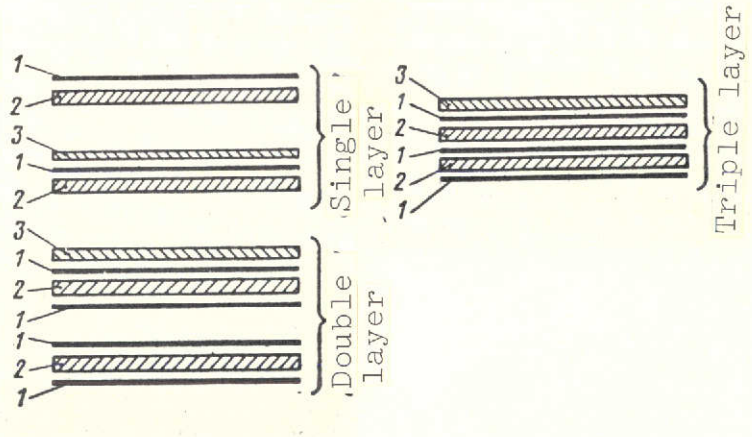


Figure 8.8. Configurations of hermetic fabrics.
1 — fabric; 2 — sealing layer; 3 — protective coating.

The chararacteristics of some rubberized fabric are shown in Table 8.4.

Depending on the thread arragment in the layers, the two-layer and three-layer rubberized fabrics are subdivided into fabrics with parallel-doubled and diagonal-doubled threads. In the parallel-doubled thread case, the warp threads in both layers

TABLE 8.4*

TECHNICAL CHARACTERISTICS OF RUBBERIZED FABRICS (MRTU38-5-6040-65)

Fabric type	Textile type	GOST	Weight of rubberized fabric, g/m²	Breaking strength no less than, kG/running meter		H_2 permeability after 24 hours, no more than, liters/m²	Delamination strength of 500 × 200 mm² strip no less than, kG/m²
				Warp	Woof		
Single-layer rubberized adhesive	Percale A	12125—66	—	—	—	—	2
Two-layer diagonal-doubled	Percale A	12125—66	300—400	800	750	4,5	3
Three-layer diagonal-doubled	Percale A	12125—66	450—490	1550	1300	2,5	3
Single-layer rubberized adhesive	Percale B	12125—66	—	—	—	—	2
Two-layer diagonal-doubled	Percale B	12125—66	220—245	480	460	4,5	3

*Commas in the numbers indicate decimal points.

are arranged in parallel, in the diagonal-doubled thread case the warp and woof threads in the different fabric layers are located at a 45° angle to one another.

The strength of the two-layer rubberized fabrics with parallel-doubled threads in uniaxial loading is approximately twice that of a single-fabric layer, however, they have reduced resistance to tearing.

TABLE 8.5*

PHYSICAL AND MECHANICAL PROPERTIES OF GLASS FABRICS

Characteristic	Magnitude of characteristic							
	Designation							
		E		A	AS	T_1	T_2	SE
	Thickness, mm							
	0,06	0,08	0,1	by agreement	0,1	0,27	0,27	0,20
Cloth weight per m^2, g	61—75	85—115	90—120	no more than 80	90—120	270—300	270—300	180—220
No. threads/cm:								
warp	19—21	19—21	19—21	19—21	19—21	15—17	15—17	9—11
woof	19—21	20—24	20—24	16—18	20—24	9—11	9—11	8—10
Breaking strength of 25 × 100 mm^2 strip in kG, no less than:								
warp	25	30	30	28	35	170	160	110
woof	20	25	30	20	35	105	85	100
Content in %, no more than	1,5	1,5	1,5	2,5	1,5	2,5	2,5	1,5

*Commas in the numbers indicate decimal points.

In addition to the required strength properties, the fabrics for the cosmonaut's outer wear should be incombustible and thermally stable, and their surface should also have the specified values of the light absorption and reflection coefficients. The fabrics made from glass fiber have good fire resistance properties. These fabrics do not lose their strength over /252
a wide temperature range. Their drawbacks include comparatively weak resistance to abrasion, high specific weight, and extreme brittleness.

The physical and mechanical characteristics of some glass fiber fabrics are shown in Table 8.5.

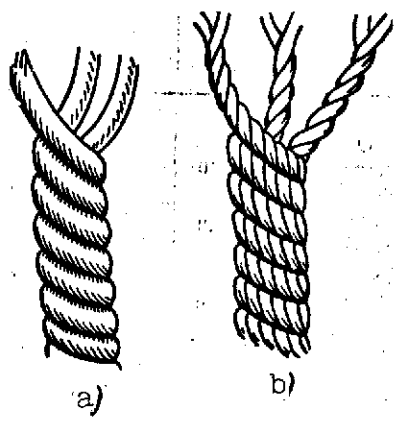


Figure 8.9. Structure of textile threads.

a — 3-strand; b — 6-strand.

Knitted materials made from cotton, cotton-linen, and woolen yarn are used to make underwear. /254

Textile Threads

Threads are used in pressure suits to join portions of the suit fabricated from various fabrics.

In order to increase strength, the threads are twisted together in 3, 4, 6, 9, and 12 strands. The 3-strand threads have single twist, the 6-strand threads have double twist (Figure 8.9).

The thread number N (in the metric system) is defined by the ratio of thread length l to its weight G, i.e., $N = l/G$, and the number indicates the number of meters of thread per gram of weight.

Thread strength characteristics are defined by the ultimate tensile strength and the breaking length (Table 8.6).

Kapron threads burn very slowly, melt, and do not smolder. Glass threads do not burn.

Tapes and Laces /255

A broad assortment of different tapes and laces are used in pressure suits as structural elements, reinforcement, and decorative details.

TABLE 8.6*

STRENGTH CHARACTERISTICS OF TEXTILE THREADS

Thread	GOST, TU, STU	Number	Strength kG	Elongation %	Wt. per 100 m g	Remarks
Linen	GOST 2350-43	9,5/5	13,5	3—3,5	50	
Linen		9,5/8	20,5	3,5	80	
Cotton	GOST 6309-59	30	1,5	5,1	5,9	3-strand
Cotton	GOST 6309-59	20	1,95	5,8	8	6-strand
Cotton	GOST-6309-59	10	2,2	6	9,8—11	"
Cotton	GOST-6309-59	0	5,8	8	24—27	12-strand
Cotton	GOST 6309-59	00	7,6	8,5	34—38	"
Kapron	TU RSFSR 17-2710-68	5,5	10	20	—	Made from 5-tex shiny kapron (No. 200)
	"	9	3,7	25	—	
	"	13	2,8	25	—	
	"	15	2,2	25	—	
	"	18	1,6	25	—	
	STU 86-12-206-62	10	4,0	25	—	
	"	7	6,7	25	—	
	"	3	11,0	25	—	
Glass NS-75/24	GOST 8325-61	3	15	1—2,5	—	
Glass NS-76/6	GOST 8325-61	12,5	4,1	—	—	
Lavsan	STU 30-12311-64	34/4	4,6	18—20	12—13,5	
	"	34/2	2,3	14—16	6—7	

*Commas in the numbers indicate decimal points.

Tapes are fabricated on tape weaving looms from warp and woof threads with cotton yarn, twisted silk, twisted kapron, lavsan, and linen threads being used for their fabrication (Figure 8.10).

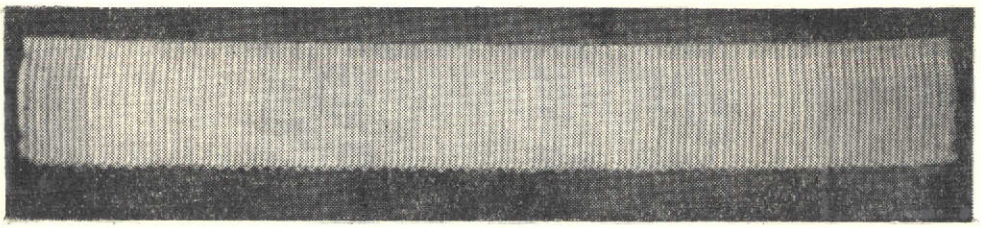


Figure 8.10. Kapron tape LTK-16-400.

TABLE 8.7*

BASIC CHARACTERISTICS OF SOME SOVIET PRODUCED TAPES

Tape type	Designation	Width mm	Breaking strength kG	Elongation %	Weight per running m, g
Kapron	LTK-8-130	8	130	25—35	4,7
	LTK-20-260	20	260	30—50	10
	LTK-10-40	10	40	25—45	1,9
	LTK-20-195	20	195	25—45	20
	LTK-9-180	9	180	25—45	6,5
	LTK-45-70	45	700	35—50	26
	LTK-12-300	12	300	35	8
	LTK-16-400	16	400	35	12
	LTK-25-600	25	600	35	14
	LTK-20-500	20	500	35	13
Cotton	LKhB-13-65	13	65	12—20	4,5
	LKhB-25-150	25	150	12—20	10

*Commas in the numbers indicate decimal points.

The Soviet nomenclature for tapes is shown in Table 8.7.

Depending on the fabrication technique, *laces* may be woven (Figure 8.11) or twisted. Some woven laces have a core consisting of several cotton, kapron, or other threads. The basic characteristics of some woven laces are shown in Table 8.8.

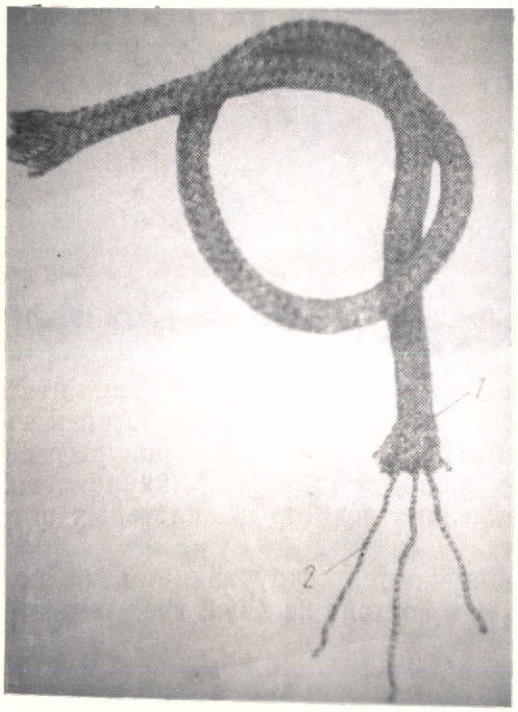


Figure 8.11. ShKP woven kapron lacing.
1 — covering; 2 — core.

Twisted laces are obtained by twisting together several uniform yarns. Most often, they consist of two, three, or four yarns.

2. Rubbers

Rubbers are used to impregnate fabrics in order to seal them and are also used to make individual detail parts (articles).

The successes achieved in synthesizing silicone rubbers having high thermal stability and chloroprene rubbers having comparatively good resistance to fire are broadening the areas of application of these materials in pressure suit construction.

Natural rubber (NR). Natural rubber is not used in pressure /256
suits. In its place, use is made of vulcanized rubber, which is the product of natural rubber vulcanization — interaction with sulfur, organic additives, and other substances. Vulcanized rubber has high elasticity, is impermeable to gases and resistant to many aggressive media. It becomes brittle at -70° C and /257
plastic at +80 — +100° C. Some grades of vulcanized rubber can be reversibly stretched by more than 1000%, and its tensile strength reaches 350 kG/cm^2. Vulcanized rubbers have low thermal conductivity (0.32 — 0.44 kcal/(m/hr/°C)).

TABLE 8.8*

BASIC CHARACTERISTICS OF SOME SOVIET PRODUCED WOVEN LACES

Cords	TU, GOST	Diameter m	Breaking strength g	Elongation, %	Weight per m, g
Kapron					
ShKP-60	TU RSFSR 17-2660-68	2,5±0,2	60	35—50	2,0
ShKP-150	"	4±0,3	150	35—50	5,5
ShKP-300	"	5±0,3	300	35—50	12,5
Cotton					
ShKhB-125	GOST 2297-43	6±1	125	20—30	13
ShKhB-60	"	3,5±0,5	60	15—30	6,5

*Commas in the numbers indicate decimal points.

The resistance of vulcanized rubber to tearing is defined as the ratio of the ultimate (tearing) load F_{tear} to the initial thickness δ_0:

$$\sigma_{tear} = \frac{F_{tear}}{\delta_0} \text{ kG/cm} \qquad (8.5)$$

The air permeability of vulcanized rubber (rubberized fabrics) is determined by creating a pressure difference of 5 — 10 mm H_2O across a test specimen of area 10 cm^2 and measuring the quantity of air passing through the specimen in liters per minute.

The specific gas permeability is the gas volume in cubic centimeters passing per second through a surface area of one square meter with layer thickness one centimeter and pressure difference 1 mm Hg [6].

The tensile moduli (effective moduli) are often used to characterize the elastic properties of vulcanized rubber. The tensile moduli for vulcanized rubber are the stresses which arise in specimens for elongations of 100, 200, 300, 400, or 500%. They are designated as σ_{100} (100 modulus) or σ_{200} (200 modulus). Accordingly, the calculation is made using the formula [6]

$$\sigma_{300} = \frac{F_{300}}{S_0} \text{ kG/cm}^2 \qquad (8.6)$$

where σ_{300} is the stress for 300% elongation; F_{300} — the load in kG for 300% elongation; S_0 — the original cross section area.

Synthetic rubbers (SR) are rubber-like materials from which vulcanized rubbers are made.

Isoprene rubbers are obtained by polymerizing isoprene in an inert solvent medium. They are practically equivalent to natural rubber in their properties.

Because of the presence of chlorine in their molecules, the *chloroprene rubbers* (nairites) (neoprenes in the USA) have limited combustibility and, in contrast with the other rubbers, burn only under the direction action of a flame. When the flame /258 is removed, their combustion terminates. They are quite resistant to oxygen and ozone, resist tearing and sunlight well, age slowly, and have good bonding capability. However, in regard to low temperature properties, the chloroprene rubbers are inferior to many synthetics.

Silicone rubbers (silicones) have good resistance to oxygen, ozone, and sunlight, the highest thermal stability, but poor resistance to abrasion. The adhesivity of the vulcanized rubber

mixture based on silicone rubber is not satisfactory.

The urethane rubbers have high strength and elasticity, high resistance to aging and tearing. The gas permeability of urethane rubber is 10 times that of natural rubber.

At the present time, Soviet industry produces vulcanizates made from synthetic rubbers which are equivalent in their physical and mechanical properties to those made from natural rubber. The properties of vulcanizate mixtures after vulcanization are shown in Table 8.9.

Rubber detail parts for breathing oxygen equipment may be selected in accordance with TU 1428-57.

Latexes. Natural and synthetic latexes and artificial rubber-natural dispersions are widely used in the production of individual pressure suit components. Use of the latexes makes it possible to fabricate seamless rubber components, knitted rubber articles, and elastic foam parts. The most rational use of the latexes is in fabricating thin-wall seamless hollow components of complex configuration. The production of such parts using conventional technology from hard natural rubber is extremely difficult or completely impossible.

Parts made from the latexes are characterized by high elasticity and low gas permeability.

Articles with good resistance to low temperatures, thermal stability, and fire resistance can be fabricated by proper selection of latex type and latex mixture composition [10].

TABLE 8.9*

PROPERTIES OF RUBBER MIXTURES AFTER VULCANIZATION [9]

(TU 1166-58, 1428-57r)

Rubber group	Rubber mixture brand	Rubber type	Ultimate tensile strength in kG/cm², no less than	Relative elongation at failure in %, no less than	Hardness using TShN-2 durometer, kG/cm2	Coefficient of aging after 144 hours at 70° C, no less than	Brittle temperature upon cooling in °C, no less than	Sp. wt., g/cm³
1	922		45	300	5—10,6	0,80	—40	1,14
	1432		40	350	4—8	0,75	—43	1,09
2	3853		90	400	10—13	0,75	—48	1,57
	B-201		120	600	—	—	—	—
	IRP-1029		150	650	—	—	—	—
	Zh		120	500	4,5—9,9	0,60	—50	1,44
3	3109-N	SKSV	80	350	6—13	0,60	—30	1,35
	2542-N		100	180	10—28	0,60	—40	1,36
	3508-N		70	450	5—11	0,7	—40	1,38
4	2651	SKS-10	50	250	5—11	0,6	—45	1,13
	14K-10		55	275	6—12	0,70	—70	1,14
	14K-22		110	100	—	—	—70	—
	4611		45	200	6—12	0,70	—65	1,17
5	3703	NR	160	350	15—20	0,70	—50	1,20
	3701		200	500	4—9	0,80	—55	1,03
	3311		150	700	3—6	0,80	—55	0,98
6	1847	NR	160	600	4—9	0,80	—55	1,05
	2959		160	500	5—10	0,80	—55	1,17
	2462	SKSV	100	300	10—21	0,70	—50	1,40
7	4094-N-1	SKB	70	30	30—70	0,60	—20	1,73
	2696		110	200	20—40	0,55	—	1,37
8	3687	NR	130	500	5—10	0,75	—55	1,28
	5168	SKB	35	200	6—11	0,70	—40	1,26
9	98-1	Nairit	50	160	7—13	—	—60	1,16
	V-14		100	160	12—19	0,70	—50	1,28
	V-14-1		120	140	15—20	—	—50	1,28
	IRP-1078		110	150	13—21	0,75	—42	1,37
	NO-68-1		90	250	7—15	—	—55	1,24
10	3819	SKTV	90	300	7—15	0,80	—45	1,25
	3826s		80	300	7—17	0,75	—27	1,35
	9722		60	500	—	0,70	—	1,30
	3825		100	120	16—33	0,80	—30	1,31
	IRP-1338		50	300	—	—	—	—

Latexes are aqeuous dispersions of rubbers, stabilized by surfactants. The rubber in latex is in the form of microscopic and ultramicroscopic particles (globules) covered by a surfactant protective layer. The particles have a negative charge (latexes with positively charged particles can be obtained for certain articles). On the basis of the origin, the latexes are divided into natural, synthetic, and artificial dispersions.

The commercial grades of natural latex are concentrates with dry material content 60 — 73%. Latex is stabilized by introducing antiseptics in order to prevent spontaneous coagulation under the influence of bacteria and also to increase latex stability with respect to chemical, mechanical, and other influences.

Soviet industry utilizes primarily the latex grades produced under the trade names kvalitex, lesantex, and so on.

With all the variety of techniques for fabricating articles from the latexes, they can be divided into two basic techniques:

— obtaining film by removal of moisture;

— obtaining film by interaction of the latex with electrolytes or other stabilizing agents.

In the first case, the technique of obtaining rubber articles by multiple dipping may be utilized. This technique involves immersing a form simulating the article in external shape into the latex mixture with subsequent withdrawal from the latex mixture, drying of the deposited gel, and redipping of the form into the latex mixture. This operation is repeated 3 — 5 times, depending on the required article wall thickness. After drying the last layer, the article is vulcanized. This /260

method finds limited application and is advisable only for use in obtaining articles with wall thickness not exceeding 0.15 to 0.20 mm.

The ion deposition method is widely used in Soviet industry. The basis of this process is the interaction of positively charged electrolyte ions with the latex protective substances. In this case, there is both removal of the negative charge from the globules upon their contact with the positively charged electrolyte ions and the formation of insoluble emulsifier salts during globule chemical interaction with the coagulant.

The ion deposition process takes place as follows. The form is immersed in the electrolyte (fixer) solution. The latter is usually a calcium chloride or calcium nitrate solution. Then the form is immersed in the latex and a latex gel film is deposited on it. The form exposure time in the latex mixture as a function of required film thickness usually lies in the range from one to fifteen minutes.

The latexes can be used to obtain rubber tricot articles.

The technique for fabricating such articles consists in treating the tricot, placed on the form, in an alcohol-acetate mixture (sometimes the article is treated without the form and the tricot blank is placed on the form after treatment) with subsequent dipping into the latex. A film is deposited on the surface of the tricot. This procedure provides one-sided application of the film without through-impregnation of the tricot material.

Foam rubbers with bulk weight from 0.08 to 0.18 g/cm^3 can be obtained from the latexes.

The technique for their production is as follows. The latex mixture is foamed mechanically and a gelatinizing agent is added to the foam. The foam is poured into a form where it gelatinizes and is then vulcanized. After vulcanization, the articles are rinsed and dried.

3. Light-Transparent Materials

Light-transparent materials are used in fabricating pressure suit helmet faceplates (visors) and light filters. These include the polymer light-transparent materials and the silicate glasses.

Polymer Light-Transparent Materials

Polyacrylates (organic glass) are fabricated in sheet form from silicate glass.

Various grades of organic glasses having high light transmission, low thermal conduction, low thermoplasticity, and good strength are used for pressure suit helmet visors. The new grades of organic glasses (ST-1, 2-55, TST-1, etc.) are easily formed, oriented, bonded, welded, and mechanically worked [11].

Orientation of organic glass is the name used to denote uniform planar stretching of the glass in the plastic (heated) state with subsequent cooling under load; the optimum elongation of the material in this process is 50 — 70%.

Orientation improves the mechanical characteristics of the glass markedly. For example, after orientation of the ST-1 glass, its tensile strength at 20° C increases from 780 to 830 kG/cm^2, relative elongation increases from 4 to 20%, impact strength goes from 13.8 to 33.3 $kG/cm/cm^2$ (Table 8.10).

TABLE 8.10*

PHYSICAL AND MECHANICAL PROPERTIES OF ORGANIC GLASSES [4]

Characteristic	Organic glass types																			
	SOL				ST-1					2-55						T-2-55				
	Temperature, °C																			
	−20	20	60	80	−60	20	60	80	100	−60	20	60	80	100	120	20	60	80	100	120
Ult. strength kG/cm²:																				
in tension	1410 1120	775 710	430 410	205 150	1440 1135	830 780	500 510	340 380	185 120	1415 1225	1080 925	700 635	535 520	335 365	160 175	1055 1000	— 730	— 580	305 370	— 215
in static bending	1540 —	1195 990	690 735	395 530	1835 —	1010 1180	565 885	425 610	235 365	1945 —	1550 1210	1075 975	745 810	555 560	350 210	1760 1200	— 1100	— 980	465 720	— 315
Tensile elastic modulus, kG/cm²	— 55000	30600 29000	19200 18000	11400 14000	— —	30900 32100	20800 23750	16200 21750	7300 12900	— —	39800 41600	28250 29300	23900 25300	18300 20500	8300 10900	39200 40800	— 30100	— 25200	14800 19100	— 12200
Rel. elongation at break, %	3,3 1,6	23,2 3,6	31,0 21,0	43,7 60	3,9 2,2	20,0 4,0	27,0 6,0	60 30,7	60 60	3,4 2,0	12,9 2,8	13,3 4,0	17,6 4,8	51,0 11,0	60 12,0	10,4 3,3	— 4,2	— 4,5	50 21,2	— 7,5
Specific impact strength, cm/cm²	25,8 14,5	25,5 13,0	29,8 14,2	36,8 15,4	31,4 14,9	33,3 13,8	39,9 14,9	49,9 15,5	200 18,2	30,5 15,7	32,0 14,8	33,1 15,3	36,2 15,6	38,7 15,9	200 16,4	28,9 15,0	— 16,5	— 16,2	23,8 17,1	— 17,4

NOTE: Numerator is value for oriented glass; denominator is value for unoriented glass.

*Commas in the numbers indicate decimal points.

TABLE 8.11*

THERMOPHYSICAL PROPERTIES OF ORGANIC GLASSES [4]

Glass mark	Softening temperature °C	Thermal conductivity, kcal/m/hr/°C	Specific heat cal/(g/°C)	Coefficient of linear expansion $\alpha \cdot 10^6/°C^{-1}$
SOL	90—95	0,158	0,3	71
ST-1	110—120	0,156	0,4	77
2-55	133—138	0,160	0,4	69
T-2-55	133—138	0,155	0,37	75,6

*Commas in the numbers indicate decimal points.

The thermophysical properties of the organic glasses are shown in Table 8.11. The optical properties of the organic glasses are given in Table 8.12.

The materials used for helmet visors must be resistant to the action of static and dynamic loads, thermally stable, and not alter their optical properties when heated.

The optical properties of materials used for visors are characterized by the magnitude of the light transmissions. It is very important that the materials be uniform, have low luminescence level, and low light scattering. The optical properties of the helmet visor should remain essentially constant in the operating temperature range and under the action of ionizing radiation. /262

The coefficient of transmission in the UV part of the spectrum increases with increase of the wavelength for all the organic glasses (Table 8.13).

TABLE 8.12***

OPTICAL PROPERTIES OF ORGANIC GLASSES [4]

Characteristic	Glass types			
	SOL	ST-1	2-55	T-2-55
Refraction coefficient				
at 21° C	1,4930	1,4895	1,4961	1,4960
at 45° C	1,4892	1,4870	1,4933	1,4945
at 60° C	1,4873	1,4848	1,4919	1,4930
at 75° C	1,4850	1,4830	1,4900	1,4910**
at 90° C	1,4825	1,4820	1,4890	1,4900
Image play in minutes	2—3	2—3	2—3	2—3
Angular shift in minutes	3—9	3—9	3—9	3—9
Light stability in %, no more than	2	2	2	2
Optical stress coefficient at 18 — 20° C, Brewsters	2,2—2,4	4,6—4,8	2,0	1,2—1,5

*Transparency reduction when glass is irradiated by PRK-2 lamp for 200 hours.

**Tests conducted at 80° C.

***Commas in the numbers indicate decimal points.

TABLE 8.13

SPECTRAL LIGHT TRANSMISSION* OF ORGANIC GLASSES [4]

Glass type	Integral light transmissivity, %	Spectral transmissivity, %																		
		UV region μ					Visible region μ		IR region, μ											
		300	320	340	360	380	400	750	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000
SOL	90—92	11	53	76	86	88	89	92	90	90	61	60	70	45	49	7	0	2	12	0
ST-1	90—92	0	0	11	85	89	90	90	92	92	90	60	69	42	49	5	1	8	20	0
2-55	90—92	0	0	0	67	85	88	90	88	88	82	50	49	25	20	2	0	3	9	0
T-2-55	90—92	0	0	0	45	74	80	90	89	90	80	60	49	33	21	3	3	4	9	2

*Measured on glass specimens 5 mm thick using SF-4, SF-2M, IKS-14, and SF-10 spectrophotometers.

The polycarbonates have high impact strength, are thermally stable, and cold resistant. They are easily formed by pressure casting, pressing, and all forms of mechanical working, are easily welded and bonded.

The basic physical and mechanical properties of diflon polycarbonate are [4]: /263

Specific weight, g/cm^3	1.2
Ultimate strength, g/cm^2:	
tension	600 — 700
compression	300 — 900
bending	1000 — 1100
Specific impact strength, kG/cm/cm^2 (unnotched)	120 — 140
Relative elongation at failure, %	80 — 100
Brinell hardness, kG/mm^2	15 — 16

Polycarbonate made from pure raw material is a transparent material (particularly in thin layers). It is self-extinguishing material and has the following thermophysical properties [4]:

Melting point, °C	235 — 275
Softening point, °C	132 — 138
Specific heat, kcal/kG/°C	0.28
Self-ignition temperature, °C	500
Cold resistance in °C	-100
Maximum working temperature, °C	135 — 137

The temperature dependence of polycarbonate ultimate strength is shown in Figure 8.12.

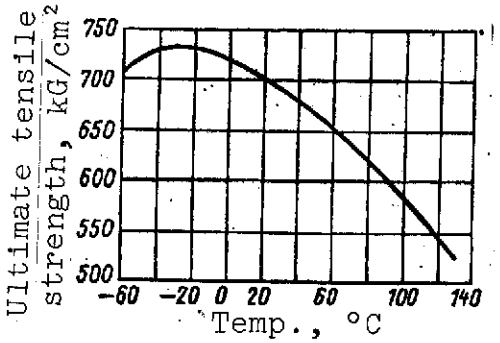


Figure 8.12. Polycarbonate ultimate strength in tension as function of temperature [4].

Silicate Glasses

Present-day optical silicate glasses have high light transmission characteristics in the visible portion of the spectrum, negligibly small light scattering, and invariability of the optical properties when heated. Visors of complex configuration with good optical characteristics can be obtained from silicate glass (by the optical grinding and polishing technique).

The radiational optical stability of special optical silicate glasses is three or four orders of magnitude higher than for the organic glasses and their luminescence is several orders lower.

Because of its high hardness, silicate glass withstands scratching well. To improve the mechanical strength of the silicate glasses, they are tempered, etched, surface coatings are applied, and so on. /264

Silicate glass is used to fabricate the very strong triplex construction, which consists of two or more plates or spheres bonded together by an organic transparent interlayer (butvar, butafol). The triplex construction combines mechanical strength, freedom from shattering upon impact, and good optical properties.

The drawbacks of silicate glass are comparatively high weight and low impact strength.

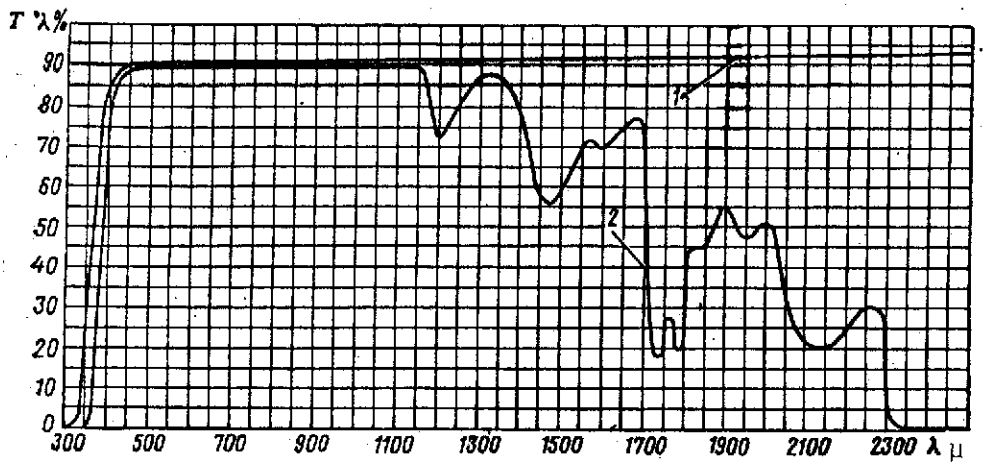


Figure 8.13. Spectral light transmission [14].
1 — silicate glass; 2 — triplexed silicate glass.

Tempered glasses are used in those cases when high mechanical strength is required along with comparatively low weight, relatively high thermal stability, and fracture safety.

Impact strength increases by a factor of three to five upon tempering and the bending strength increases by 5 to 6 times. Glass impact strength testing should be done on finished articles with account for the nature of their mounting.

The properties of the silicate glasses are presented below.

	Range
Specific weight, g/cm^3	2.2 — 3
Ultimate strength:	
in tension and static bending, kG/cm^2	200
in impact bending, kG/cm/cm^2	2 — 2.5
Elasticity modulus of lst kind in kg/mm^2	6000 — 8000
Relative fracture elongation in %	fractions of 1%
Specific heat, cal/(g/°C)	0.08 — 0.25

	Range
Coefficients:	
Thermal conductivity, cal/(sec/cm/°C)	0.0010 — 0.0032
Thermal conductivity, kcal/(hr/m/°C)	0.3 — 1.2
Thermal diffusivity, cm^3/sec	0.0063 — 0.0010
Thermal diffusivity, m^3/hr	0.0024 — 0.0004
Coefficient of linear expansion, deg^{-1}	$(5 — 150)\cdot10^{-7}$
Thermal stability, °C	50 — 100

The spectral transmission of silicate glass is shown in Figure 8.13.

4. Polymer Films

Polymer films, both oriented and unoriented, of thickness from 2 to 200 microns have high elasticity, mechanical strength, and resistance to the ambient medium.

Polymer films are used in pressure suit construction to fabricate the vacuum barrier thermal insulation (VBTI) and for packing. The sorption properties of some films may also be used. For example, polyethylene films have low moisture permeability but pass carbon dioxide and air.

Polyester films based on polyethylene terephthalate (PETP film) form a transparent and elastic material with strong surface luster. The film is odorless and very strong, therefore it can be fabricated in thicknesses down to 5 — 12 microns. It has high tear, impact, and abrasion strength. The film withstands more than 2×10^4 reversals prior to breaking. /265

The high strength of the PETP films is retained at temperatures from -60 to +150° C. Long-term heating at 150° C reduces the mechanical strength only slightly, and these films retain stability of form even at 180 — 200° C. Under long-term action of low temperatures (down to -70° C), the properties of these films remain practically constant; even at the temperature of liquid air, the film does not lose flexibility. The film is practically impermeable to gases and does not transmit the biologically active shortwave portion of the solar spectrum. It melts at 240 — 260° C.

The specific heat capacity of the film at 25° C is 0.315 cal/g [4]; the thermal conductivity is $3.63 \cdot 10^{-4}$ cal/(cm/sec/°C). PETP film can be bonded by an adhesive consisting of a 4% solution of TF-60 resin (VTU II-264-66) in methylene chloride [4].

An aluminum layer 0.01 — 0.02 micron thick is applied to its surface on one or both sides under hard vacuum conditions to improve the optical properties of the film. The emissivity of the aluminized surface is no more than 0.05 (65TU-67) (film emmisivity 0.3 — 0.4). The values of the absorption A_s and radiation ε (emissivity) coefficients for different films are shown in Table 8.14.

The physical and mechanical characteristics of some films are presented in Table 8.15.

5. Thermoprotective Materials

Thermoprotective materials are divided into fibrous, granular, and cellular (foam).

TABLE 8.14***

VALUES OF THE ABSORPTION COEFFICIENT A_s AND EMISSIVITY ε

FOR SOME FILM MATERIALS

Film	Film thickness μ	A_s	ε	A_s/ε
Polyethylene	60	0,01	0,18	0,055
Melinex*	12,5	0,01	0,26	0,0385
Terylene	20	0,01	0,35	0,0285.
Polyethylene terephthalate	12	0,02	0,3—0,4	0,667—0,50
Aluminum-metallized polyethelene terephthalate	12	0,12	0,03—0,04	4,0—3,0
Gold-metallized mylar**	—	0,12	0,06	2,0

*Melinex is a polyethylene-glycol-terephthalate film.

**Mylar is a polyethylene-glycol-tetraphthalate film.

***Commas in the numbers indicate decimal points.

TABLE 8.15

PHYSICAL AND MECHANICAL CHARACTERISTICS OF SOME FILMS [4,5]

Film	Spec.	Specific weight g/cm³	Thickness μ	Breaking strength kG/cm²	Relative elongation %	Temperature range °C
Polyethylene	MRTU6-05-1042-67	0.92-0.93	26-70	no less than 160	no less than 300	from -70 to +110
PETP	MRTU6-05-1108-68	1.3-1.4	5-60	1300-1500	no less than 50	from -60 to +150
Polyamide PK-4	TU UKhP No. 17-58	—	50-70	300-600	—	—

The fibrous thermoprotective materials include various products made from wool, synthetic fibers, and glass fiber.

Insulation consisting of ultrafine glass fiber (0.7 — 1.5 μ) with unloaded density 5 — 6 kG/m^3 has excellent thermal insulating properties; its thermal conductivity is about 0.025 kcal/(m/hr/°C). /266

In textile materials, there is air between the yarn fibers, and therefore the thermal conductivity of textile materials is determined not so much by the thermal conductivity of the fibers themselves as by the volume of the air pores in the threads and fabrics. Thus, the magnitude of the thermal conductivity depends on fabric structure to a greater degree than on the thermal conductivity of the fibers, and the hermetic resistance of the fabric is proportional to the amount of air present in the fabric. Therefore, from the viewpoint of thermal protection, preference should be given to those materials (fabrics) whose structure ensures their incompressibility and remains constant under all operating conditions. The excellent thermal protection properties of wool are explained precisely by the fact that, under all conditions, wool maintains a constant thickness of the air layer present in the wool.

Wool knit material is used in fabricating the thermal protective lining or the thermal protection garment. The basic characteristics of this material are shown in Table 8.16.

ATIM-9 (ML and PPTU 218-53L) felt is made from high quality sheep's wool in sheet form with different thicknesses. The specific weight of ATIM-9 felt is about 0.14 g/cm^3 that of ATIM-8 felt is about 0.09 g/cm^3. Felt can be used at temperatures from -60 to +120° C, it burns only weakly, after removal of the flame source, its burning terminates. /267

The anti-meteorite shell can also be made of wool felt.

TABLE 8.16

PHYSICAL AND MECHANICAL PROPERTIES OF THERMOPROTECTIVE MATERIALS

Material	Thickness mm	Weight per m^2/g	Breaking strength of 50 × 200 mm^2 strip kG		Elongation at failure %		Thermal conductivity kcal/(m^2/hr/°C)	Thermal resistance (m^2/hr/°C/kcal)
			*	**	*	**		
Wool tricotage fabric (art. 211)	1.25	330	34	17	95	185	0.08	0.015
Wool tricotage fabric with nappe	4.0	460	17.5	18	75	170	0.045	0.09
Wool fabric with porolon threads	4.0	475	33	25	90	80	0.052	0.07

*Lengthwise

**Transverse

Figure 8.14 shows the thermal conductivity of various materials versus air pressure. We see from the figure that significant increase of the thermal conductivity occurs even at a pressure of $7.5 \cdot 10^{-3}$ mm Hg.

Granular (powdered) thermoprotective materials are used primarily to insulate containers with liquified gases.

Among the cellular materials, porous rubber and foam plastics have found widest use in pressure suit construction.

Porous rubber (R-30) STU 49-2565-63 is produced in the form of plates with thin outer films and closed pores. In one cubic meter of rubber, there are 20,000 cells, whose average wall thickness is 0.012 mm, and the thermal conductivity is about 0.028 kcal/(m/hr/°C) at +15° C.

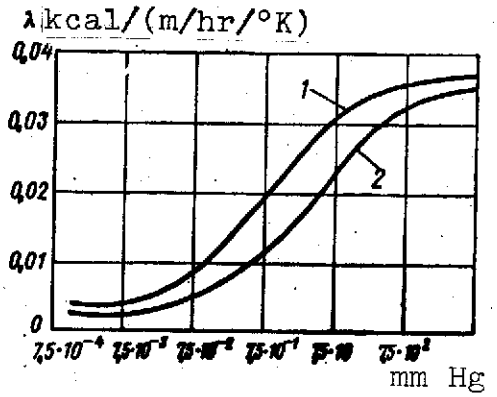


Figure 8.14. Thermal conductivity of thermoprotective materials versus air pressure [15].

1 — glass fiber material;
2 — granular materials.

Low density porous rubber is used as thermal insulating, pressure sealing, and thermal protective material. This rubber is produced in plate form. The rubber designation is OM-12 (VTU 1211-1002), the volumetric weight of the rubber is no more than 0.2 g/cm^3. The tensile strength is no less than 10 kG/cm^2. The relative elongation at break is about 250%. The thermal conductivity is about 0.035 kcal/(m/hr/°C).

The OM-12 rubber burns with release of materials which are harmful to the human organism in the form of carbon monoxide, nitrogen, and so on. The burning properties of the rubber increase with presence of pure oxygen in the medium. The physical and mechanical properties of the rubber deteriorate under vacuum conditions. The operating temperature range is from -50 to +50° C. /268

Foamed plastics. Gas-filled (foamed) plastics can be obtained from nearly all the known polymers. They differ from the monolithic plastics in lightness, good thermal and sound insulation properties.

On the basis of their structure, the gas-filled plastics are divided into two groups: materials with closed pores (phenoplasts) and materials with open (communicating) pores (poroplasts).

PS-1 (MRTU 6-05-1178-69) phenoplast is made from polystyrene. The compressive ultimate strength is no less than 8 kG/cm^2, volumetric weight is 100 kG/m^3, specific impact strength is no less than 1.1 kG/cm/cm^2. Operating temperature is ±60° C. The sound absorption coefficient of PS-1 phenoplast is 0.02 — 0.05. The thermal conductivity depends on the bulk weight of the phenoplast and lies in the range from 0.025 to 0.04 kcal/(m/hr/°C).

PS-1 phenoplast is used for sound insulation and also as flotation and packing material. The drawback of this material is its flammability.

PVKh-1 and PVKh-2 (MRTU 6-05-1179-69) phenoplasts are made from polyvinyl chloride. They have low flammability and therefore are used in fabricating survival equipment.

PU-101 (STU 35-KhP-674-64) phenoplast is made from polyester. It is used in making articles which are resistant to the action of gasoline, kerosene, and organic oils.

PPU-E-25-1.8 (MRTU 6-05-1150-68) polyurethane elastic poroplast is produced with volumetric weight 25 kG/m^3, average cell (pore) size 1.8 mm, ultimate tensile strength 1.2 kG/cm^2, relative elongation at break no less than 150%.

The elastic poroplasts are used in fabricating shock absorbing linings, as thermal insulating layers, and also for protecting the breathing organs in dust-trapping filters.

6. Adhesives

Adhesives are used in pressure suit construction for strong and hermetic joining of textile materials and metals between

themselves and with nonmetallic materials, and also nonmetallic materials (plastics, rubbers, etc.) with one another.

It is practically impossible to classify the adhesives with regard to their application areas, since the same adhesives are used for bonding various materials in articles for the most varied purposes.

At the present time, it is customary to classify the adhesives on the basis of whether the primary component is a thermoreactive or thermoplastic polymer [13].

In most cases, the heat resistant adhesive bonds used in fabricating load bearing structures made from metals and nonmetallic materials are based on the thermoreactive resins (phenolformaldehyde, epoxy, etc.).

Adhesives having relatively low strength characteristics, particularly when used under elevated temperature conditions, are based on the thermoplastic resins (polyisobutylene, polyvinyl acetate, etc.). These adhesives are used primarily for nonstructural joining of nonmetallic materials.

The rubber adhesives, which are adhesive compositions based on elastomers (primarily natural rubbers), have high elasticity and are used for bonding rubbers with one another and rubbers /269
with metals.

The strength of the adhesive joint is determined by the adhesion — the bonding between the adhesive substance and the surface being glued. In considering adhesion, we must also take into account cohesion — the bonding within the adhesive materials.

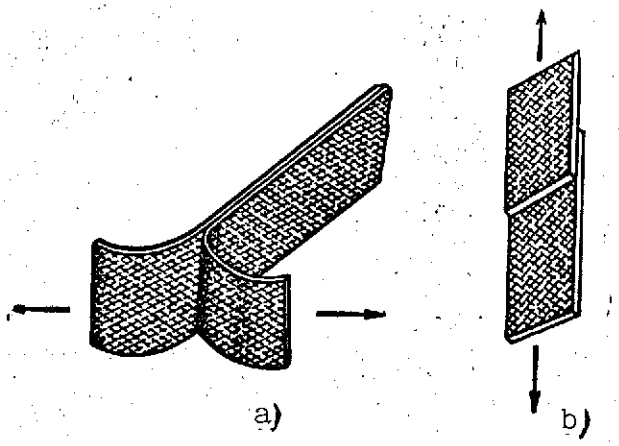


Figure 8.15. Adhesive seam testing scheme.

a — delamination; b — shear.

In studying the strength of the bond between two bodies, we customarily use the method of determining the strength in uniform tension, and the method of testing strength in delamination and shear is also widely used.

Determination of adhesive seam strength in delamination and shear is accomplished using the scheme shown in Figure 8.15.

The delamination resistance index is calculated using the formula

$$\sigma_{del}=\frac{F_{del}}{b}\ kG/cm \qquad (8.7)$$

where F_{del} is the force acting in kG; b — the specimen width in cm.

Determination of adhesive seam strength in shear is made using the formula

$$\sigma_{sh}=\frac{F_{sh}}{S}\ kG/cm^2 \qquad (8.8)$$

where σ_{sh} is the unit ultimate shear load in kG/cm^2; F_{sh} — the load causing specimen failure in kG; S — the contact area in cm^2.

Rubber adhesives are divided into nonvulcanizing and vulcanizing types.

The first group includes the adhesives based on natural rubber, and thermoprene, which are solutions of the indicated polymers in organic solvents. The bonding strength of the non-vulcanizing adhesives is relatively low.

Adhesive 4508 (TU MKhP 1105-50) is a solution of 4508 rubber mixture in gasoline. This adhesive is intended for bonding vulcanized rubbers and cotton fabrics.

The bonding strength of the adhesive in delamination should be no less than 3 kG for a strip 5 cm wide consisting of two bonded strips of calico or sheeting material.

The 88N (MRTU 38-5-880-66) nairit adhesive is used in bonding vulcanized rubbers to metal, glass, and other materials, and also to cold-bond rubber with rubber. Articles bonded using the 88N adhesive can be used in sea water.

The strength of the 88N adhesive bond in delamination of rubber from steel or aluminum should be no less than 2 kG/cm, and the tensile strength should be 11 kG/cm^2.

The 88NP adhesive (MRTU 38-5-6022-65) is a solution of /270
the rubber mixture No. 31-NP and butylene formaldehyde resin in a mixture of ethyl acetate and gasoline.

The 88NP adhesive is intended for cold-bonding of various rubbers to metals and also rubber to rubber, operating in the temperature range from -50 to +70° C.

The basis of the *thermoprene adhesive* is a thermally treated mixture of natural rubber and phenol sulfate. This adhesive is used for bonding metal to unvulcanized rubbers.

Normal strength is reached after 10 to 20 days at standard temperature and after 1 to 2 days at +50° C.

The adhesives of the second group contain vulcanizing substances in addition to the rubbers. Stronger adhesive bonds are obtained after vulcanization in comparison with the non-vulcanizing adhesives.

Vulcanization is carried out both at 140 — 150° C and at 25 — 30° C (in the latter case, the adhesives are called self-vulcanizing and their composition includes accelerators and activators).

The SV-1 self-vulcanizing adhesive (leuconate adhesive) MRTU 38-5-6064-65) consists of two components: the basic solution (4508 adhesive) and the vulcanizing agent solution. It is used for bonding rubber articles operating at temperatures up to 100° C. The pot life of the SV-1 adhesive is no less than four hours.

The SV-2a self-vulcanizing adhesive (TU No. 38-5-390-69) consists of two components: the SV-2 adhesive and a vulcanizing compound (leuconate adhesive). The SV-2 adhesive is a solution of a nairit rubber mixture in a mixture with solvents (ethyl acetate and gasoline). The pot life of the SV-2a adhesive is no less than eight hours. This adhesive is used for bonding rubbers and rubberized fabric articles.

The KT-30* cold vulcanization adhesive, and also the silicone sealants of the Viksint-U-1-18 and Viksint-U-2-28 types are used for bonding heat-resistant silicone rubbers.

*Heat-resistant silicone adhesive VTU P-63-64.

Nearly all the polymer materials, after being subjected to special surface treatment, can be bonded by the polyurethane (PU-2) and polyepoxy base adhesives which harden under normal conditions. However, the bonds made using cold setting adhesives may not be sufficiently strong under operating conditions, particularly at elevated temperatures [13].

The VZ1-F9 and PU-2 adhesives are used to bond organic glass articles with one another and with dacron and lavsan tapes.

The E-2 heat resistant organic glass is bonded with itself and also with lavsan tape by the VS-10TM adhesive. Bonding of organic glass using a 2 — 5% solution of the glass in dichlorethane has also been used.

Leather and its substitutes are bonded with one another and with other materials with the aid of rubber, perchlorvinyl, and polyurethane adhesives; some polyamide base adhesives are also used. The strongest bonds are obtained by using the polyurethane compositions (PU-2 adhesive, for example).

The BF-6 phenol-polyvinyl-butyral adhesive and the PVB-K-1 polyvinyl-butyral adhesive are used for bonding fabrics and other textile materials.

Both hot and cold setting adhesives of various types (L-4, VK-9, VS-10T, BF-2, PU-2, VK-1, VK-3, and so on) are used to bond metals with nonmetallic materials (glass cloths, phenoplasts, and so on) and also for bonding metals with one another.

Prior to bonding, the inert materials (teflon and polyethylene) are subjected to special chemical treatment, after which they are bonded using conventional adhesive compositions.

7. Fire Resistance and Flammability of Materials

Improvement of the fire resistant properties of the materials used in pressure suits is of great practical importance.

The fabrics made from cellulose fibers* ignite rapidly and burn upon contact with a heat source of sufficient intensity. Cellulose fibers may also smolder, i.e., burn without flame. /271 This smoldering may lead not only to destruction (breakdown) of these materials, but also to fire, since smoldering often takes place unnoticed and then flame may break out as the combustible gaseous fractions accumulate.

Woolen and silk fabrics are less combustible in comparison with fabrics made from the cellulosic fibers. They do not smolder and when exposed to flame, they carbonize and sinter into a mass which then falls apart.

Artificial acetate silk sinters into a solid glassy lump with the release of an unpleasant odor. Viscose burns more intensely than cotton. Kapron fabric melts and burns. Chlorinated polyvinyl chloride fabric burns only in a flame. Table 8.17 shows the flammability characteristics of some fabrics.

Studies have shown that, with the increase of the oxygen partial pressure in the atmosphere, and also with increase of the overall pressure of a gaseous medium, the ignition (self-ignition) temperature, the minimum ignition energy, and the

*Cotton fiber contains 94 — 95% cellulose.

TABLE 8.17

FLAMMABILITY CHARACTERISTICS OF SOME MATERIALS [16]

Material	Ignition temperature in air, °C	Nature of combustion in air
Cotton	520	Burns rapidly, bright flame
Flax	600	Same
Wool	800	Burns slowly, in bursts. Burning stops away from flame
Natural silk	—	Same
Viscose	—	Burns rapidly, bright flame
Acetate fiber	—	Burns rapidly, bruning stops away from flame
Kapron	1000	Softens in flame and then melts (at t = 215° C) and burns in bursts
Lavsan	1000	Same. Melting point about 260° C.
Rubber IRP-1029	800	
Kid leather	650	

ignition delay time* decrease for most materials and the burning rate increases (Figure 8.16).

We can conclude that use in pressure suits of an atmosphere enriched with oxygen and particularly an atmosphere of pure oxygen requires marked increase of the designers' attention to the problems of ensuring maximum fire safety.

The percentage content of the inert gases in the surrounding /272 medium and their nature affect the combustion process. The results of combustion studies in nitrogen-oxygen and helium-oxygen atmospheres conducted in the USA are shown in Table 8.18.**

*The ignition delay time is the time from initiation of heating to the instant of ignition.

**Technology Week, Vol. 20, No. 5, January 30, 1967.

TABLE 8.18*

FLAME PROPAGATION RATE FOR BURNING OF VARIOUS MATERIALS IN DIFFERENT ATMOSPHERES

Material	Flame propagation rate for material burning in various atmospheres, mm/sec						
	Air (760 mm Hg)	20% O_2, 80% He (760 мм mm Hg)	46% O_2, 54% N_2 (380 мм mm Hg)	46% O_2, 54% He (380 мм mm Hg)	70% O_2, 30% N_2 (258 мм mm Hg)	70% O_2, 30% He (258 мм mm Hg)	100% O_2 (258 мм mm Hg)
Wood	0,6±0,6	1±0,1	3±0,5	4,5±0,8	4,5±0,8	6,8±0,8	8,9±0,8
Paper	2±0,2	8±1,5	10±0,5	16±1,2	14±1,2	19±1,5	23±1,7
Cellulose acetate	0,2±0,1	—	2,8±0,2	4±0,5	5±0,8	4,5±0,5	8±0,2
Cotton fabric	2,5±0,2	4±0,2	23±8	28±2	45±5	30±5	81±5
Foam plastic	3,5±0,5	0	68±20	53±8	154±13	152±15	330±25
Wire in plastic insulation	0	0	6,3±0,2	9±0,5	12±0,2	15±0,5	21±0,8
Painted surface	0	0	5,3±0,2	7±0,2	8±0,5	10±1,5	11±1,3

*Commas in the numbers indicate decimal points.

The experiments were conducted in a cylindrical chamber 37 cm in diameter, 84 cm long, and have a volume of 0.09 m^3. The specimens were ignited by a hot wire and radiation. The experimental results permit drawing the following conclusions.

1. Flame propagation takes place faster in the helium-oxygen atmosphere than in the nitrogen-oxygen atmosphere.

2. The flame propagation velocity is independent of the atmosphere pressure in the range studied (258 — 760 mm Hg).

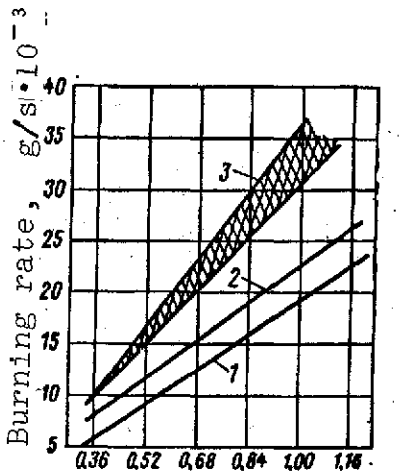


Figure 8.16. Burning rate as function of oxygen partial pressure in mixture with nitrogen [16].

1 — phenylon; 2 — lavsan; 3 — kapron.

3. Significant increase of the energy required for ignition of the material was observed in the oxygen-helium atmosphere. /273

Fabrics are impregnated chemically with special compounds in order to increase their fire resistance, and this may provide complete inflammability of the fabric for local action of a high temperature ignition source. Material which has been properly treated chars and breaks down when exposed to fire, but after the flame is removed, the material does not burn or smolder. In the case of short-time exposure of a fire resistant material to a flame, only the region immediately in contact with the flame is noticeably damaged [17].

REFERENCES

1. Buzov, B. A., N. N. Pozhidayev, et al. Laboratornyy praktikum po materialovedeniyu shveynogo proizvodstva (Laboratory Course in Material Science for the Garment Industry), Legkaya industriya, Moscow, 1964.

2. Moncrieff, R. W. Chemical Fibers (Russian translation), Izd-vo nauchno-tekhn. literatury, Moscow, 1961.

3. Tikhomirov, V. B. Netkanyye kleyenyye materialy (Nonwoven Bonded Materials), Legkaya industriya, Moscow, 1966.

4. Spravochnik po plasticheskim massam (Plastics Handbook), edited by M. I. Garbar et al., Vol. 1, Moscow, Khimiya, 1967.

5. Spravochnik po plasticheskim massam (Plastics Handbook), edited by M. I. Garbar et al., Vol. 2, Moscow, Khimiya, 1969.

6. Belozerov, N. V. Tekhnologiya reziny (Rubber Technology), Khimiya, Moscow, 1967.

7. Kukin, G. N. and A. N. Solov'yeva, Tekstil'noye materialovedeniye (Textile Material Science), Vol. 3, Legkaya industriya, Moscow, 1967.

8. Zherebkov, S. K. Krepliniye reziny k metallam (Bonding Rubber to Metals), Khimiya, Moscow, 1966.

9. Chernyak, K. I. Nemetallicheskiye materialy v sudovoy elektro- i radiotekhnicheskoy apparature (Nonmetallic Materials in Marine Electrical and Radio Equipment), Sudostroyeniye, Moscow, 1966.

10. Noble, R. G. Latex in Engineering (Russian translation), State Scientific and Engineering Publishing House for Chemical Literature, Moscow, 1962.

11. Perov, B. V. and M. M. Gudimov. Oriyentirovannoye organicheskoye steklo (Oriented Organic Glass), Oborongiz, Moscow, 1961.

12. Reznikovskiy, M. M. and A. I. Lukomskaya. Mekhanicheskiye ispytaniya kauchuka i rezina (Mechanical Tests of Caoutchouc and Rubber), Khimiya, Moscow, 1964.

13. Kardashev, D. A. Sinteticheskiye klei (Synthetic Adhesives), Khimiya, Moscow, 1968.

14. Spravochnik po proizvodstvu stekla (Handbook on Glass Production), State Publishing House of Literature on Construction, Architecture, and Construction Materials, Moscow, 1963.

15. Modestova, T. A., L. N. Flerova, and B. A. Buzov. Materialovedeniye shveynogo proizvodstva (Material Science for the Garment Industry), Legkaya industriya, Moscow, 1969.

16. Abduragimov, I. M., B. B. Serkov, and S. A. Yantovskiy. Kosmicheskiye issledovaniya, Vol. 9, No. 6, 1971.

APPENDIX

TABLE A.1

STANDARD ATMOSPHERE TABLE (GOST 4401-64)

Altitude m	Temp °C	Barometric pressure		Density		
		mbar	mm Hg	kG/m^2	kG/m^3	$kG/sec^2/m^4$
−2 000	28,04	1277,9	958,50	13031,0	1,4781	$1,5072 \cdot 10^{-1}$
−1 000	25,52	1139,27	854,52	11617,4	1,3469	$1,3735 \cdot 10^{-1}$
0	15,00	1013,25	760,00	10332,3	1,2250	$1,2492 \cdot 10^{-1}$
500	11,75	954,53	715,96	9733,5	1,1672	$1,1902 \cdot 10^{-1}$
1 000	8,5	898,76	674,12	9164,8	1,1117	$1,1336 \cdot 10^{-1}$
1 500	5,25	845,66	634,30	8623,3	1,0582	$1,0791 \cdot 10^{-1}$
2 000	1,99	794,98	596,28	8106,5	1,0066	$1,0265 \cdot 10^{-1}$
2 500	−1,26	746,93	560,24	7616,6	$9,5706 \cdot 10^{-1}$	$9,7593 \cdot 10^{-2}$
3 000	−4,51	701,25	525,98	7150,8	$9,0941 \cdot 10^{-1}$	$9,2734 \cdot 10^{-2}$
3 500	−7,77	657,74	493,35	6707,1	$8,6345 \cdot 10^{-1}$	$8,8048 \cdot 10^{-2}$
4 000	−11,02	616,56	462,46	6287,2	$8,1942 \cdot 10^{-1}$	$8,3558 \cdot 10^{-2}$
4 500	−14,27	577,49	433,15	5888,8	$7,7714 \cdot 10^{-1}$	$7,9246 \cdot 10^{-2}$
5 000	−17,52	540,45	405,37	5511,1	$7,3654 \cdot 10^{-1}$	$7,5106 \cdot 10^{-2}$
5 500	−20,77	505,35	379,04	5153,1	$6,9758 \cdot 10^{-1}$	$8,1134 \cdot 10^{-2}$
6 000	−24,02	472,13	354,13	4814,4	$6,6022 \cdot 10^{-1}$	$6,7324 \cdot 10^{-2}$
6 500	−27,27	440,69	330,54	4493,8	$6,2441 \cdot 10^{-1}$	$6,3672 \cdot 10^{-2}$
7 000	−30,52	410,98	308,26	4190,8	$5,9010 \cdot 10^{-1}$	$6,0174 \cdot 10^{-2}$
7 500	−33,77	382,90	287,20	3904,5	$5,5725 \cdot 10^{-1}$	$5,6824 \cdot 10^{-2}$
8 000	−37,01	356,48	267,38	3635,1	$5,2591 \cdot 10^{-1}$	$5,3628 \cdot 10^{-2}$
8 500	−40,26	331,47	248,62	3380,1	$4,9585 \cdot 10^{-1}$	$5,0563 \cdot 10^{-2}$
9 000	−43,51	307,91	230,95	3139,8	$4,6712 \cdot 10^{-1}$	$4,7633 \cdot 10^{-2}$
9 500	−46,75	285,79	214,36	2914,2	$4,3977 \cdot 10^{-1}$	$4,4844 \cdot 10^{-2}$
10 000	−50,00	264,91	198,70	2701,3	$4,1357 \cdot 10^{-1}$	$4,2172 \cdot 10^{-2}$
10 500	−53,25	245,28	183,98	2501,2	$3,8859 \cdot 10^{-1}$	$3,9625 \cdot 10^{-2}$
11 000	−56,49	226,90	170,90	2313,7	$3,6485 \cdot 10^{-1}$	$3,7204 \cdot 10^{-2}$
11 500	−56,49	209,76	157,33	2139,0	$3,3728 \cdot 10^{-1}$	$3,4393 \cdot 10^{-2}$
12 000	−56,49	193,91	145,44	1977,0	$3,1180 \cdot 10^{-1}$	$3,1795 \cdot 10^{-2}$
13 000	−56,49	165,72	124,30	1689,9	$2,6648 \cdot 10^{-1}$	$2,7173 \cdot 10^{-2}$
14 000	−56,49	141,64	106,24	1444,3	$2,2776 \cdot 10^{-1}$	$2,3225 \cdot 10^{-2}$
15 000	−56,49	121,07	90,810	1234,6	$1,9467 \cdot 10^{-1}$	$1,9851 \cdot 10^{-2}$
20 000	−56,49	55,269	41,450	563,59	$8,8870 \cdot 10^{-2}$	$9,0623 \cdot 10^{-3}$
25 000	−56,49	25,262	18,948	267,6	$4,0621 \cdot 10^{-2}$	$4,1422 \cdot 10^{-3}$
30 000	−42,8	$1,1836 \cdot 10^{-1}$	8,8777	120,69	$1,7901 \cdot 10^{-2}$	$1,8254 \cdot 10^{-3}$
40 000	−15,49	2,9586	2,2191	30,169	$4,0003 \cdot 10^{-3}$	$4,0792 \cdot 10^{-4}$
50 000	−0,85	$8,4581 \cdot 10^{-1}$	$6,3441 \cdot 10^{-1}$	8,6249	$1,0754 \cdot 10^{-3}$	$1,0966 \cdot 10^{-4}$

TABLE A.2

PROPERTIES OF ATMOSPHERIC AIR (see Chapter 5 of [10])

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Temperature °C	Weight/m^3 at barometric pressure 760 mm Hg, kG	H_2O vapor content at barometric pressure 760 mm Hg and total saturation in kG	
		per m^3 air	per kG of moist air
—20	1,396	0,0011	0,0008
18	1,385	0,0013	0,0009
16	1,374	0,0015	0,0011
14	1,363	0,0017	0,0013
12	1,353	0,0020	0,0015
10	1,342	0,0023	0,0017
88	1,332	0,0027	0,0020
6	1,322	0,0031	0,0024
4	1,312	0,0036	0,0028
2	1,303	0,0042	0,0032
0	1,293	0,0049	0,0038
2	1,284	0,0056	0,0043
4	1,275	0,0064	0,0050
6	1,265	0,0073	0,0057
8	1,256	0,0083	0,0066
10	1,248	0,0094	0,0075
12	1,239	0,0107	0,0086
14	1,230	0,0121	0,0098
16	1,222	0,0136	0,0112
18	1,213	0,0154	0,0127
20	1,205	0,0179	0,0144
22	1,197	0,0194	0,0163
24	1,189	0,0218	0,0184
26	1,181	0,0244	0,0207
28	1,173	0,0272	0,0234
30	1,165	0,0304	0,0263
32	1,157	0,0338	0,0295
34	1,150	0,0376	0,0331
36	1,142	0,0417	0,0370
38	1,135	0,0462	0,0414
40	1,128	0,0511	0,0463
42	1,121	0,0565	0,0516
44	1,114	0,0623	0,0575
46	1,107	0,0687	0,0640
48	1,100	0,0756	0,0711
50	1,093	0,0831	0,0790
52	1,086	0,0911	0,0877
54	1,080	0,0998	0,0972

TABLE A.3*

BASIC PHYSICAL CHARACTERISTICS OF GASES

Substance	Chemical formula	Molecular weight m	Specific weight kG/m³	Density relative to air	Mole volume nm³/mol	Temperature, °C			Critical pressure per kG/cm²
						Boiling (t_b)	Melting (t_m)	Critical (t_{cr})	
Nitrogen	N_2	28,016	1,2505	0,9673	22,4	—195,81	—210,02	—147,0	34,6
Ammonia	NH_3	17,031	0,7714	0,6967	22,08	—33,4	—77,7	—132,3	115,0
Acetylene	C_2H_3	26,04	1,1709	0,9057	22,22	—83,6	—81	35,7	63,7
Acetone	C_3H_6	58,08	(2,595)	2,005	(22,41)	56,1	—94,3	235,5	48,1
Hydrogen	H_2	2,0156	0,8987	0,06952	22,43	—252,78	—259,2	—239,9	13,2
Air (dry)		28,96	1,2928	1,000	22,4	—193	—213	—140,7	38,4
Helium	He	4,003	0,1785	0,1381	22,42	—288,93	—	—267,9	2,33
Carbon dioxide	CO_2	44,01	1,9768	1,5291	22,26	—78,48	—56	31,04	75,28
Nitrous oxide	N_2O	44,016	1,9780	1,53	22,05	—88,7	—90,8	36,5	74,1
Hydrogen iodide	HI	127,93	5,789	4,478	22,1	—36	—51	150	83,7
Oxygen	O_2	32,000	1,42895	1,033	22,39	—182,97	—218,83	118,4	51,7
Methyl alcohol	CH_4O	32,04	1,426	1,103	22,47	64,51	—98	240	81,1
Nitric oxide	NO	30,008	1,3402	1,0367	22,39	—152	—163,5	—93	66,1
Carbon monoxide	CO	28,01	1,2500	0,9669	22,40	—191,5	—205	—140	35,6

*Commas in the numbers indicate decimal points.

TABLE A.4

WATER VAPOR PRESSURE IN AIR IN mm Hg FOR DIFFERENT HUMIDITIES [19]

Temperature of air and skin, °C	Relative humidity, %							
	30	40	50	60	70	80	90	100
0	1,4	1,8	2,3	2,8	3,2	3,7	4,1	4,6
5	2,0	2,6	3,2	2,9	4,6	5,2	5,9	6,5
10	2,7	3,6	4,6	5,4	6,3	7,2	8,2	9,2
12	3,1	4,2	5,2	6,2	7,3	8,3	9,4	10,4
14	3,5	4,7	6,0	7,0	8,2	9,4	10,8	11,7
16	4,0	5,4	6,7	8,1	9,4	10,8	12,9	13,5
18	4,5	6,0	7,5	9,0	10,5	12,0	13,4	15,0
20	5,0	6,8	8,5	10,2	11,9	13,6	14,6	17,0
22	5,8	7,8	9,8	11,7	13,6	15,7	17,3	19,6
24	6,7	8,8	11,1	13,4	15,6	17,8	20,0	22,2
26	7,5	10,0	12,2	15,0	17,5	20,0	22,0	25,0
28	8,4	11,2	14,0	16,8	19,6	22,4	25,2	28,1
30	9,4	12,6	15,8	18,8	22,0	25,3	28,4	31,5
32	10,6	14,2	17,6	21,3	24,7	28,4	31,6	35,3
34	12,3	15,8	19,8	24,6	28,6	31,6	35,6	39,5
36	13,3	17,7	22,1	26,6	31,0	35,4	40,0	44,2
38	14,8	19,7	24,6	29,6	34,4	39,4	44,2	49,3
40	16,4	22,3	24,4	32,9	38,2	44,6	49,4	54,7
42	18,2	24,3	30,4	36,4	42,4	48,6	54,8	60,7
44	20,1	26,9	33,7	40,3	47,0	53,9	60,8	67,4
46	22,4	29,9	37,2	44,8	52,2	59,2	62,7	74,7
48	24,2	33,1	41,3	49,5	57,7	66,2	74,4	82,7
50	27,8	37,0	46,2	55,5	64,5	74,0	83,2	92,5

TABLE A.5*

RELATIONSHIPS BETWEEN PRESSURE MEASUREMENT UNITS

Unit	N/m^2	kG/m^2; mm H_2O	kG/cm^2	kG/mm^2	bar (hecto-piez)	mm Hg (torr)
1 N/m^2	1	0,102	$1,02 \cdot 10^{-6}$	$1,02 \cdot 10^{-7}$	10^{-5}	$7,5 \cdot 10^{-3}$
1 kG/m^2	9,81	1	10^{-4}	10^{-6}	$9,81 \cdot 10^{-5}$	$7,356 \cdot 10^{-2}$
1 mm H_2O						
1 kG/cm^2	$9,81 \cdot 10^4$	10^4	1	10^{-2}	0,981	$7,356 \cdot 10^{-2}$
1 kG/mm^2	$9,81 \cdot 10^6$	10^6	100	1	98,1	$7,356 \cdot 10^{-4}$
1 bar (hectopiez)	10^5	$1,02 \cdot 10^4$	1,02	$1,02 \cdot 10^{-2}$	1	750
1 mm Hg (torr)	133	13,6	$1,36 \cdot 10^{-3}$	$1,36 \cdot 10^{-5}$	$1,33 \cdot 10^{-3}$	1
1 acoustic bar	—	—	$1 \cdot 10^{-6}$	—	$\sim 1 \cdot 10^{-6}$	—

*Commas in the numbers indicate decimal points.

Translated for National Aeronautics and Space Administration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California 93108.